Arnold Schwarzenegger
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LANDFILL GAS-FUELED HCCI DEMONSTRATION SYSTEM

PIER FINAL PROJECT REPORT

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards $62 million to conduct the most promising public interest research by partnering with research, development, and demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

Landfill Gas Fueled HCCI Demonstration System is the final report for the Landfill Gas Fueled HCCI Demonstration project (grant # PIR-02-003) conducted by Makel Engineering, Inc. The information from this project contributes to Biomass/Renewable Energy research for Advanced Biogas Systems or Advanced Anaerobic Digestion Technologies Program.

For more information on the PIER Program, please visit the Energy Commission's Website at www.energy.ca.gov/pier or contact the Energy Commission at (916) 654-5164.

Abstract

A demonstration system has been developed intending to meet the California Energy Commission's primary goal of improving California's electric energy cost/value by providing a low-cost, high-efficiency distributed power generation system that operates on landfill gas as fuel. The project team led by Makel Engineering, Inc., includes UC Berkeley, CSU Chico and the Butte County Public Works Department.

The team has developed a reliable, multi-cylinder homogeneous charge compression ignition (HCCI) engine by converting a Caterpillar 3116, 6.6-liter diesel engine to operate in HCCI mode. This engine uses a simple and robust thermal control system. Typically, HCCI engines are based on standard diesel engine designs with reduced complexity and cost based on the well-known principles of engine dynamics. Coupled to an induction generator, this HCCI genset allows for simplified power grid connection.

Testing with this HCCI genset allowed for the development of a control system to maintain optimal the inlet temperature and equivalence ratio. A fuel to electricity efficiency of 35.0 percent was achieved while producing less than 5.0 ppm (0.07 lb/MW-hr) of NOx and 25 kW of electrical power. Higher efficiency and power output was achieved with slightly higher (~10.0 ppm) nitrous oxide production. Lower NO_X emissions were achieved (3 to 4 ppm) with slightly lower system efficiencies. The HCCI genset operated for up to 95 hours continuously with stable operation. An analysis of the components predicted >12,000 hours between major overhauls.

Testing was conducted with natural gas, simulated landfill gas, and actual landfill gas as a fuel source. Approximated 400 hours of testing was conducted with both natural gas and simulated landfill gas as a fuel source at MEI's testing facility in Chico, CA. The demonstration engine was then relocated to the Neal Road Solid waste facility in Butte County where further testing with actual landfill gas was carried out for an additional 510 hours. This demonstration system has shown that landfill gas-fueled homogeneous charge compression ignition engine technology is a viable pathway for distributed power generation with low BTU value fuels.

Keywords: HCCI, low NO_X, lean burn diesel, LFGTE, distributed power generation

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Executive Summary

Introduction

Homogeneous compression combustion ignition (HCCI) is a technology with increasing interest for distributed power generation. Recently, the development of HCCI engines has become more widespread. Relative to spark ignition (SI) engines, HCCI engines are more efficient, approaching the efficiency of a diesel engine. This improved efficiency results from three sources: the elimination of throttling losses, the use of high diesel-like compression ratios, and a shorter combustion duration. Compared to diesel engines, HCCI engines have substantially lower emissions of particulate matter (PM) and nitrogen oxides (NO_X). These low emissions are a result of the dilute homogeneous mixture and low combustion temperatures. Compared to SI engines, HCCI engines have lower maintenance costs because they operate at lower peak pressures, do not have spark plugs, and do not require expensive exhaust cleanup components. Because HCCI engines offer low maintenance, high efficiency, and low NO_X emissions, they are well-suited for distributed power applications. In addition, dilution levels can be much higher than the levels tolerated by either SI or diesel engines, making HCCI a good candidate for low energy content fuels, such as landfill gas.

Purpose

This demonstration is intended to meet the Energy Commission primary goal of improving California's electric energy cost/value by providing a low-cost, high-efficiency distributed power generation engine that uses landfill gas (LFG) as a fuel source. In addition, this demonstration helps improving the environmental and public health costs/risk of California's electricity generation by efficiently using LFG to generate electricity, while removing methane - a potent greenhouse gas - from the environment.

Project Objectives

This project sought to install an HCCI genset and related generation equipment as a demonstration of the HCCI performance characteristics while meeting the following performance goals:

- Air Emissions – NOx (ppm) [lb/MW-hr] <5.0 [0.07]
- Affordability - COE ($/kWh) <$0.05
- Capital Costs - Prime Mover ($/kW) <$750
- Prime mover lifetime on landfill gas (hours) >10,000
- Stability +/- 10%
- System Efficiency >35%

Outcomes

Makel Engineering, Inc. (MEI), has developed a reliable, multi-cylinder Homogeneous Charge Compression Ignition (HCCI) engine by converting a 6-cylinder Caterpillar 3116, 6.6 liter diesel engine to operate in HCCI mode. This engine, coupled to an induction motor, produces electricity by using low BTU-value gases as fuel. A simple and robust control system maintains optimal the inlet temperature and air-to-fuel ratio. Researchers tested for about 400 hours with both natural gas and simulated landfill gas as a fuel source at MEI's testing Facility in Chico, CA. The demonstration engine was then relocated to the Neal Road Solid Waste Facility in Butte County where further testing with actual landfill gas was carried out for an additional 510 hours.

The HCCI genset operated below 5 ppm (0.07 lb/MW-hr) NO_X emissions with about 35 percent system efficiency. Higher system efficiency was also achieved, resulting however at slightly increased NO_X emissions levels. Lower NO_X emissions were achieved (3 to 4 ppm) with slightly lower system efficiencies. The HCCI genset meets the program goal of less than 10 percent variation in engine performance.

Efficiency testing demonstrated that the genset meets project goals for efficiency and emissions. The HCCI genset meets the project goals for stability as well. To demonstrate stability, five long duration runs and sixty daily runs were performed. Stability tests were performed at three different efficiencies, with repeated tests at the optimal efficiency versus NO_X conditions (i.e., nominal 35% efficiency with 5 ppm NOx emissions).

Monitoring engine performance was ongoing for all testing. The HCCI genset was operated for daily runs (6-10 hours) and for extended runs (24-hour to 95-hour-long intervals). The engine performance was monitored for efficiency and power output while meeting project emission goals. Researchers monitored the engine for decreased performance and oil degradation but found no degradation. A closer look at the engine components revealed that the HCCI genset has a useful life of greater than 12,000 between major replacements or repairs.

Testing demonstrated that the control system in place maintains the intake at prescribed temperatures, therefore controlling ignition timing and ensuring stable operation. There are two main levels of temperature control: one to control the bulk intake temperature, and the second level, targeting optimization, is the individual control of each cylinder intake to a prescribed profile. Results of both levels of control were presented.

The long duration runs ranged from 25 to 95 hours, during which there was significant variation of the ambient condition. As the results showed, the engine stability remained unaffected by the variations in ambient temperature, dew point, and relative humidity. Results also demonstrated that the engine can operate at LFG methane contents much lower than the nominal content, without affecting stability.

MEI has estimated the following costs the genset under development: prime mover cost, interconnection costs and annual operation and maintenance costs. Table 1 summarizes the costs associated with a 30-kW production HCCI genset.

Table 1 – Costs for HCCI Gensets

Input Values	Value	units
Prime Mover Cost (BOM)	18,000	dollars
Interconnection Cost	2,350	dollars
Engine Output	30	kW
Annual Service Costs (Labor)	1,978	dollars
Annual Service Costs (Materials)	3,891	dollars
Useful life	20	years
Operational days per year	328	days

Through continued HCCI engine development and volume production efficiencies, it is anticipated that the program cost targets of $0.05/kWh and $750/kW can be achieved. A summary of the anticipated cost for production HCCI genset's is in Table 2.

Table 2 – Levelized Cost of Electricity for HCCI Genset

Target Parameter	Program Goal	HCCI Genset
LCOE ($/kWh)	< $0.05	$0.047
Capital Costs - Prime Mover ($/kW)	< $750	$745

Conclusions

At the beginning of this project, most HCCI engines were operated in laboratory environments. Field testing of this LFG fueled HCCI demonstration engine has allowed for optimization of an engine to operated in HCCI mode. By working through the several configurations, MEI has established the necessary operating conditions to meet the program goals. Using natural gas for this "tuning" of the engine allowed for testing to continue using simulated landfill gas. MEI has expanded the understanding of HCCI mode of engine operation allowing for the transition from natural gas to simulated landfill gas to eventually landfill gas as a fuel source.

Testing results demonstrated that the HCCI genset meets project goals for efficiency, emissions, stability, and durability. Operation on LFG had the following results:

- System Efficiency
  - ~35%-nominal (peak ~39 percent)
  - Program Target 35 percent or greater

- NO_X Emissions
  - ~5.0 ppm-(0.07 lb/MW-hr) nominal with 35% efficiency
  - Peak ~13.0 ppm at peak efficiency
  - Program Target 5.0 ppm or lower

- Power Output
  - ~26 kW-nominal (peak ~29 kW)

- Stability
  - <5 percent variation
  - Program target <10 percent
- Durability
  - >12,000 hours
  - Program target >10,000 hours between overhauls

Recommendations

MEI has successfully operated a demonstration HCCI genset using landfill gas. This progress marks the next step towards a commercial HCCI genset. As part of the commercial development of this HCCI genset, MEI recommends that other facilities where low BTU-value feedstocks are present (dairies, wastewater treatment plants, biomass gasification plants) install and perform testing to demonstrate the viability of this technology for each site. MEI is making this size genset (30 kW) commercially available as a demonstration engine. Initially these sites will benefit from electrical power savings by offsetting some of their electrical usage. A larger 200 kW version is being developed. When this version is ready to be launched, sites will be able to sell their excess power to the grid.

Benefits to California

Installation of HCCI engines at landfills and other sources of low BTU value feedstock sites across California can improve the quality and reliability of power supply, and will provide environmental benefits. Utilizing the gas as a fuel rather than burning it off, reduces reliance on fossil fuels, while producing very low emissions. The benefits of RD&D efforts in HCCI Genset technology include:

- Improving air quality
    - Using landfill gas (removes CH4 from environment potent greenhouse gas)
- Reduce operational costs of end user
    - Offsetting the cost of electricity for municipalities and other end users

This technology can be adopted very quickly by a wide array of potential sites where sources of low BTU value feedstock is present. These sites include:

- Landfills
- Wastewater Treatment Plants
- Dairies
- Biomass Gasification Plants

Additionally due to the very low emissions of this engine, pollutants are reduced compared to other forms of power generation:

- Improve environmental conditions for the local communities in which air quality issues exist.
- Improve the power independence for the state.
- Reduce costs for end use authorities.
- Increase revenue for landfill authorities.

1.0 Introduction

1.1 Background and Overview

1.1.1 Motivation

This demonstration is intended to meet the Energy Commission primary goal of improving California's electric energy cost/value by providing a low-cost high-efficiency distributed power generation engine that utilizes landfill gas (LFG) as a fuel source. In addition, this demonstration enables improving the environmental and public health costs/risk of California's electricity generation by efficiently using LFG to generate electricity, while removing methane - a potent green house gas - from the environment.

1.1.2 Technology Background

Relative to spark ignition (SI) engines, HCCI engines are more efficient, approaching the efficiency of a diesel engine. This improved efficiency results from three sources: the elimination of throttling losses, the use of high diesel-like compression ratios, and a shorter combustion duration (since it is not necessary for a flame to propagate across the cylinder). Relative to diesel engines, HCCI engines have substantially lower emissions of particulate matter (PM) and Nitric Oxides (NO_X) [1-3]. These low emissions are a result of the dilute homogeneous mixture and low combustion temperatures. Because flame propagation is not required, dilution levels can be much higher than the levels tolerated by either SI or diesel engines. Combustion is induced throughout the charge volume by compression heating due the piston motion, and it will occur in almost any fuel/air/exhaust-gas mixture once the 800 to 1100 K (depending on the type of fuel) ignition temperature is reached. Additionally, the combustion duration in HCCI engines is much shorter than in diesels since it is not limited by the rate of fuel/air mixing, giving HCCI engines an efficiency advantage. HCCI engines offer the potential to be lower cost than diesel engines since they would likely use lower-pressure fuel-injection equipment.

1.2 Project Objectives

This project sought to install an HCCI genset and related generation equipment as a demonstration of the HCCI performance characteristics while meeting the following Performance Goals:

Table 3 - HCCI Engine Test Platform Specifications

Target Parameter	Program Goal
Air Emissions – NOx (ppm)	<5.0
Affordability - LCOE ($/kWh)	<$0.05
Capital Costs - Prime Mover ($/kW)	<$750
Prime mover lifetime on landfill gas (hours)	>10,000
Stability	+/- 10%
System Efficiency	>35%

1.2.1 Technical Performance Objectives

- Demonstrate the market-ready potential of HCCI Engine technology as a low-cost, high-efficiency source of distributed electric power generation.
- Demonstrate the technology's contribution to both improving environmental and human health conditions through utilizing LFG as a feedstock thus removing methane from the atmosphere where it is a potent greenhouse gas.
- Demonstrate the real-world effectiveness of HCCI engine technology utilizing LFG in terms of efficiency (both emissions and power), stability (consistent engine performance over time) and durability (acceptable average time between overhauls).

1.2.2 Economic Performance Objectives

- Demonstrate a reduction in cost of electricity generation by 50% to <0.05 $/kWh
- Demonstrate a reduction in the cost of system installation to <750 $/kW
- Demonstrate the longevity of these systems at >10,000 hours between overhauls

1.3 Report Organization

This report is organized as follows:

- Project Approach
  - Project Start-up Tasks
  - Technical Tasks
  - Reporting Tasks
- Project Outcomes
  - Design
  - Engine Retrofitting
  - Baseline Testing with Natural Gas
  - Baseline Testing with Simulated Landfill Gas
  - Landfill Installation
  - Landfill Operation - Tuning
  - Landfill Operation – Testing
- Conclusions and Recommendations
  - Conclusions
  - Commercialization Potential
  - Recommendations
  - Benefits to California

2.0 Project Approach

This section presents a brief description of the project tasks, including technical and administrative activities.

2.1 Task 1.0 Project Start-up Tasks

2.1.1 Task 1.1 Attend Kick off Meeting

The goal of this task is to identify procedures for communication and reporting project status during the contract.

2.1.2 Task 1.2 Document Matching Funds

The goal of this task is to document the match funds for this agreement.

2.1.3 Task 1.3 Identify and Obtain Required Permits

The goal of this task is to obtain all permits required for work completed under this agreement in advance of the date they are needed to keep the project schedule on track.

2.2 Task 2.0 Technical Tasks

2.2.1 Task 2.1 HCCI Engine Design, Modify and Build

The goal of this task is to design, specify, procure, modify, and build the HCCI engine for use throughout the tests. The engine design will be based on the conversion of a stock CIDI engine, which provides suitable compression ratio for HCCI operation. The engine will be modified to eliminate fuel injector and to accommodate a homogenous charge introduced in the air intake. A control system with additional sensors needed to monitor the operation of the engine in HCCI mode will be added to the engine a HCCI controller will replace the stock engine controller. A thermal conditioning system shall be designed to preheat the premixed air/LFG charge to required inlet temperature. Successful completion of this task will be measured by the physical modification and construction of the engine and all it's supporting components. Meeting this goal helps achieve the project objectives by preparing the test platform for both the laboratory based test plan and field based demonstration.

2.2.2 Task 2.2 Bench Test Plan Preparation

The goal of this task is to describe in detail the instrumentation, data collection and analysis the recipient will use to set a baseline performance of the HCCI engine running on natural gas and LFG. This goal helps to achieve the project objectives by providing a clear and well-defined test plan for the next phase of the project.

2.2.3 Task 2.3 Baseline Testing with Natural Gas

The goal of this task is to set a baseline level of performance of the HCCI engine running on natural gas. The collection and documentation of a complete set of test results will measure successful completion of this task. This goal helps to achieve the project objectives by setting a baseline performance of the specific test platform of HCCI Engine which will be the test platform for both the laboratory based LFG test plan and field based demonstration.

2.2.4 Task 2.4 Bench Testing with Simulated LFG

The goal of this task is document an initial level of performance and variance from the baseline of the test platform HCCI Engine running on simulated LFG. The collection and documentation of a complete set of test plan results will measure successful completion of this task. This goal helps to achieve the project objectives by document an initial level of performance and variance from the baseline of the test platform HCCI Engine which will be the test platform for both the laboratory based simulated LFG test plan and field based demonstration.

2.2.5 Task 2.5 Install LFG Collection System

The goal of this task is to install a LFG collection system as part of the partial closer plan of Butte County's Neal Road Landfill Facility. Successful completion of this task will be measured by the construction of the LFG collection system. This goal helps to achieve the project objectives by using a host site for the demonstration of the HCCI engine's performance; efficiency, stability and longevity.

2.2.6 Task 2.6 Install LFG Engine Delivery Manifold

The goal of this task is to design, specify, procure and install the delivery manifold for use throughout the field demonstration. Successful completion of this task will be measured by the construction of the delivery manifold and integrating the manifold to the HCCI engine. This goal help to achieve the project objectives by preparing the LFG delivery system for field based demonstration.

2.2.7 Task 2.7 Install Instrumentation and Engine

The goal of this task is to install the HCCI engine and required instrumentation on site for use throughout the filed demonstration. Successful completion of this task will be measured by the physical installation of both the HCCI engine and it's instrumentation

This goal helps to achieve the project objectives by preparing the test platform and measurement tools for capturing all data during the field based demonstration

2.2.8 Task 2.8 Tune Engine On-site to run on LFG

The goal of this task is to tune the HCCI engine on-site to run on LFG. Successful completion of this task will be measured by the HCCI engine's ability to run consistently on LFG collection system and manifold. This goal helps to achieve the project objectives by finalizing the test platform in preparation for ongoing efficiency, stability and longevity testing.

2.2.9 Task 2.9 Field Test Plan Preparation

The goal of this task is to describe in detail the instrumentation, data collection and analysis. Successful completion of this task will be measured by completeness of the test plan including:

- A description of the process to be tested
- The rationale for why the tests are required
- Predicted performance based on calculations or other analyses
- Test objectives, technical approach and test matrix
- A description of the facilities, equipment, instrumentation required to conduct the tests
- A description of tests, data analysis and quality assurance procedures
- Contingency measures to be considered if the test objectives are not met

This goal helps to achieve the project objectives by providing a clear and well-defined plan for the remaining field demonstration.

2.2.10 Task 2.10 Efficiency Testing

The goal of this task is to document the HCCI engine's efficiency performance. The collection and documentation of a complete set of test plan results will measure successful completion of this task. This goal helps to achieve the project objectives by documenting real world efficiency performance of the on-site demonstration HCCI Engine.

2.2.11 Task 2.11 Stability Testing

The goal of this task is to document the HCCI engine's stability performance. The collection and documentation of a complete set of test plan results will measure successful completion of this task. This goal helps to achieve the project objectives by documenting real world stability performance of the on-site demonstration HCCI Engine.

2.2.12 Task 2.12 Durability Testing

The goal of this task is to document the HCCI engine's longevity performance. The collection and documentation of a complete set of test plan results will measure successful completion of this task. This goal helps to achieve the project objectives by documenting real world longevity performance of the on-site demonstration HCCI Engine.

2.2.13 Task 2.13 Technology Transfer Activities

The goal of this task is to develop a plan to make the knowledge gained, experimental results and lessons learned available to decision-makers in industry and government.

2.2.14 Task 2.14 Production Readiness Plan

The goal of the plan is to determine the steps that will lead to the mass manufacturing of the technologies developed in this project.

2.2.15 Critical Project Reviews

Critical Project Reviews are meetings between the Recipient, the Energy Commission Project Manager and other individuals selected by the Energy Commission Project Manager to provide objective, technical support to the Energy Commission. Meeting participants may include PIER Program Team Lead, Grants and Loans Officer, Energy Commission Technical Staff and Management. The purpose of these meetings is to discuss with the Recipient the status of the project and its progress toward achieving its goals and objectives.

Critical Project Reviews (CPR) for this project during or at the conclusion of the following tasks:

CPR1 Task 2.1 HCCI Engine Design and Build
CPR2 Task 2.4 Bench Testing with Simulated LFG
CPR3 Task 2.8 Tune Engine On-site to Run on LFG

2.3 Task 3.0 Reporting Tasks

2.3.1 Task 3.1 Monthly Progress Reports

The objective of this task is to periodically verify that satisfactory and continued progress is made towards achieving the research objectives of this program.

2.3.2 Task 3.2 Final Report

The objective of this task is to provide a public document reporting the approach and achievements of the entire program.

2.3.3 Task 3.3 Final Meeting

A final meeting for project closeout will be attended by, at a minimum, the Recipient and the Energy Commission Project Manager. The technical and administrative aspects of agreement closeout will be discussed at the meeting, which may be two separate meetings at the discretion of the Energy Commission Project Manager.

Table 4 – Documents and Meetings Resulting from Each Task

Task	Type	Title
Task 1.1	Meeting	Kick-off meeting
Task 1.2	Document	Matching funding documentation
Task 1.3	Document	List of permits
	Document	Copy of permits
Task 2.1	Document	Engine Design Documentation Report (Design Package)
	Meeting	Critical Project Review 1
Task 2.2	Document	Bench Test Plan
Task 2.3	Document	Natural Gas Baseline Testing Interim Report
Task 2.4	Document	Simulated LFG Testing Interim Report
	Meeting	Critical Project Review 2
Task 2.5	Document	Report on the Installation of LFG Collection System
Task 2.6	Document	Report on the Installation of Delivery Manifold
Task 2.7	Document	Report on the Installation of Engine and Instrumentation
Task 2.8	Document	On-site Engine Performance Interim Report
	Meeting	Critical Project Review 3
Task 2.9	Document	Field Test Plan
Task 2.10	Document	Efficiency Testing Interim Report
Task 2.11	Document	Stability Testing Interim Report
Task 2.12	Document	Longevity Testing Interim Report
Task 2.13	Document	Technology Transfer Plan
Task 2.14	Document	Production Readiness Plan
Task 3.1	Document	Monthly Progress Reports
Task 3.2	Document	Final Report Outline
	Document	Final Report
Task 3.3	Meeting	Final Meeting

3.0 Project Outcomes

This project consisted of converting a standard diesel engine to operate in HCCI mode, and demonstrate its operation using LFG as the fuel. The results are described in the following sections, from the design stages to retrofitting, bench testing, culminating with over 500 hours of operation at the Neal Road Landfill (NRL). The NRL field tests demonstrated that all the technical performance objectives were met, namely efficiency, emission and stability targets. The analysis presented shows that the economic objectives were met as well.

3.1 Design

The HCCI genset has been developed as a stationary power generation system powered by a modified diesel engine operating in HCCI mode. This generator system consists of the following components: a modified fixed displacement reciprocating engine, an electric generator, thermal conditioning system for air-fuel (A/F) mixture, instrumentation/actuators, and an automated control system. These components are described in the following sections.

The HCCI genset, shown in Figure 1, consists of a simplified stock CAT 3116 engine coupled to a generator. Modifications to the stock engine include: the addition of partitions to the intake manifold cover and the replacement of stock intake with an individual cylinder temperature control (ICTC) manifold. Appropriate generator housing was selected to couple directly to the SAE 14 bell housing of the engine. Table 5 lists the genset specifications.

Table 5 – Genset Specifications

Parameter	Specification
Cylinders	6 (In-line)
Compression Ratio	16.7 : 1
Displacement	6.6 L
Oil Sump Capacity	21 Quart
Cooling	Air-Liquid (DEAC)
Turbocharged	1.5 ATM
Engine RPM	1800 RPM
Maximum Output Power (electric)	35 kW
Generator	Induction 440 VAC, 3-phase, 60 Hz
Size	5.0’ X 8.0’ X 6.0’
Weight	2800 lb

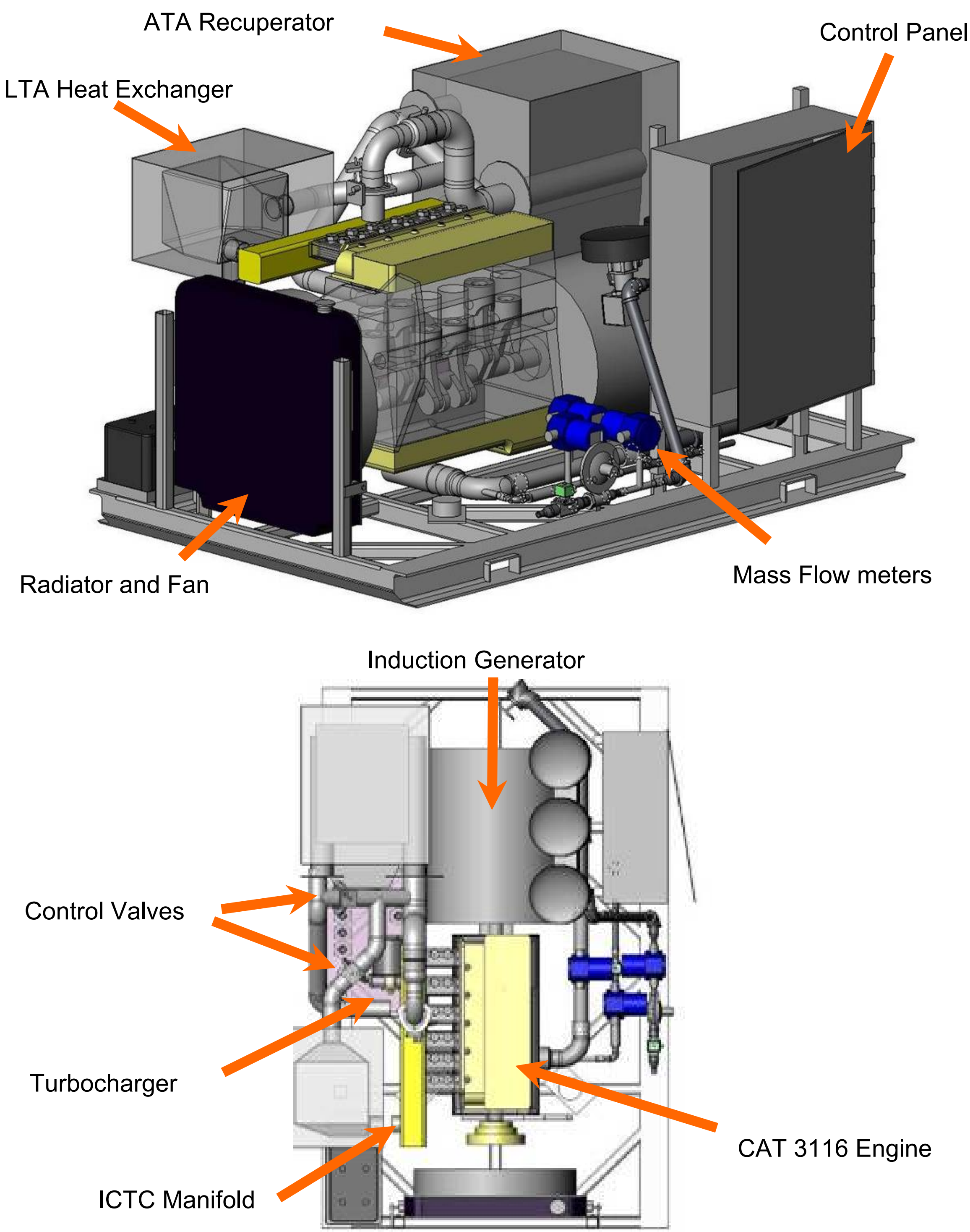


Figure 1 – Genset Overview

3.1.1 Intake System

In an HCCI engine, there is no spark plug and no fuel injector, and thus, no direct control of ignition timing. Combustion is accomplished by compression heating of the air-fuel charge in the cylinder to achieve auto-ignition. Ideally, this would occur when the cylinder is at top dead center (TDC). The primary control variable for sustaining operation in HCCI mode is the engine's intake temperature. To adjust the cylinder inlet temperature, a unique thermal conditioning system has been developed. It is comprised of intake ducts and valves, an air-to-air (ATA) heat exchanger, a liquid-to-air (LTA) heat exchanger, an ICTC manifold and heat transfer oil (HTO) reservoir.

Thermal Conditioning

The thermal control of the LFG HCCI system is the primary means to control ignition timing of the engine. The system is designed with two heat exchanger systems to accommodate startup and steady state operation. The LTA heat exchanger coupled with a hot oil pump and reservoir allow for the proper intake temperature at startup to be reached. Once the engine is producing exhaust hot gases, the ATA heat exchanger provides the necessary heat input and the LTA heat exchanger is bypassed.

A heated 10-gallon reservoir allows for the pumping of heat transfer oil (HTO) through the LTA heat exchanger. Initially, the oil is heated by six 2.0 kW, 208 VAC electric heaters to provide thermal energy to warm up the A/F mixture prior to the intake. Once the engine starts, the hot exhaust is used in the ATA heat exchanger to provide the required thermal energy. This transition takes place gradually, as the engine warms up, and at steady state, the heaters are no longer utilized. The required intake thermal energy comes from the waste heat generated by the engine. Re-configuration of the intake ducting allowed for the use of butterfly valves to control inlet temperature rather than HTO temperature.

ICTC Manifold

For optimization of power output and system efficiency, a means to adjust the inlet temperature to each cylinder is required [4]. To supply each cylinder with a slightly elevated or decreased inlet temperature, the ICTC manifold was developed. Figure 2 shows the manifold and the internal heating mechanism of an individual runner of the ICTC manifold. The main components of the ICTC include 200 Watt heaters and thermocouple probes.

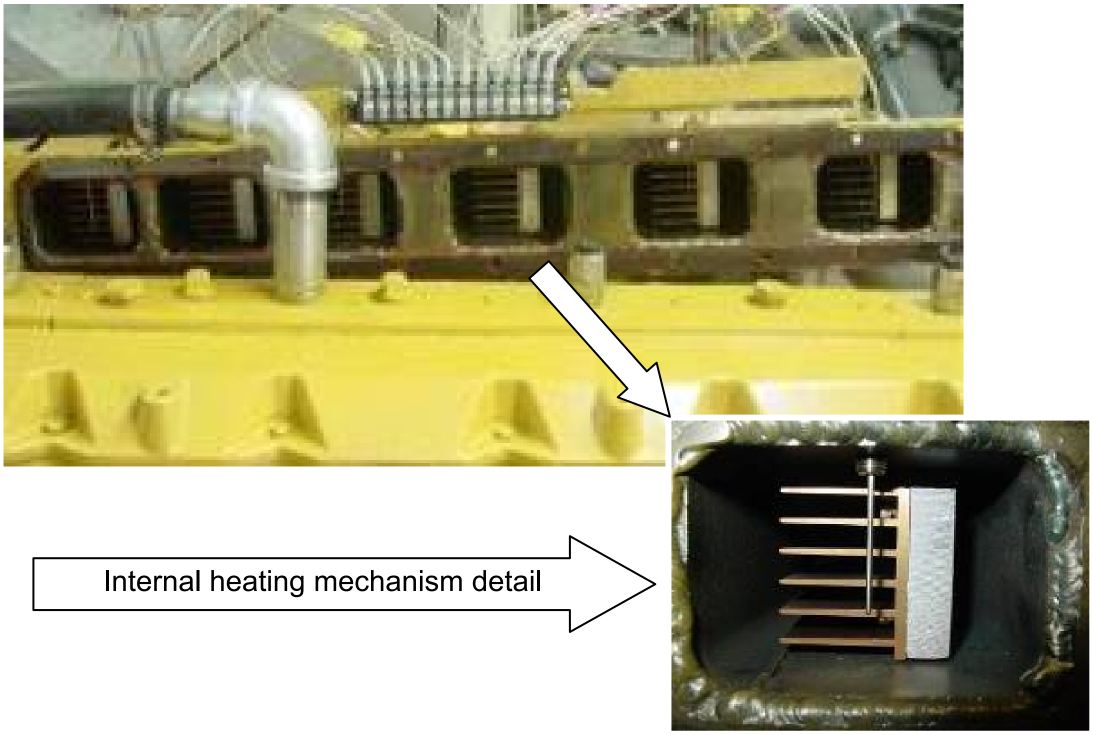


Figure 2 – ICTC Manifold

Turbocharger

A turbocharger has the following components: compressor housing, compressor impeller, bearing housing, turbine shaft and turbine housing. Figure 3 indicates pressures P_1, P_2, P_3 and P_4 flowing into and out of a turbocharger. The pressure of the intake charge entering the compressor side of the turbocharger is defined as P_1. The pressure of the intake charge leaving the compressor side of the turbocharger heading toward the engine intake is defined as P_2. The pressure of the exhaust gases prior to entering the turbine side of the turbocharger is defined as P_3. The pressure of the exhaust gases prior to entering the turbine side of the turbocharger is defined as P_4. The MAP is recorded in the engine intake. These pressures were measured and used to compute the performance parameters of the turbocharger.

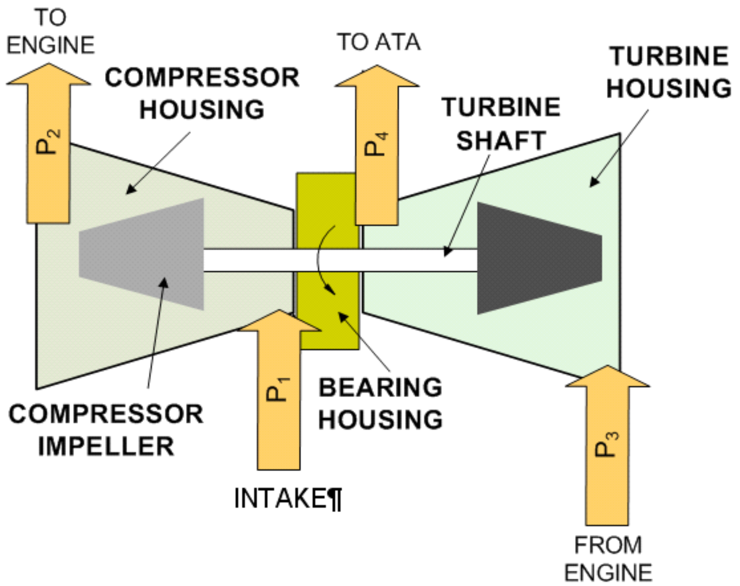


Figure 3 – Turbocharger Diagram

There are thousands of different turbine, compressor, and compressor impeller combinations. Testing started with the stock CATERPILLAR turbocharger (iteration #1) sized for a diesel engine with about half the displacement or 3.0 L of the CAT 3116 engine. Each turbocharger investigated was characterized by the following performance parameters: air flow, pressure ratio, boost and back pressure. Air flow, measured in kilograms per hour, quantifies the amount of air turbocharger pulls through the intake. Boost is the amount of pressure increase as measured by the manifold absolute pressure sensor in the engine intake. Pressure ratio is the pressure increase across the compressor side of the turbocharger. Back pressure is the amount of pressure the turbine side of the turbocharger exerts on the engine exhaust manifold. Pressure ratio (P_r) and back pressure (P_b) are computed in Equation 1 and Equation 2 [6]:

Pressure Ratio $$P_r = \frac{P_2}{P_1}$$ **Equation 1**

Back Pressure $$P_b = \frac{P_3}{P_4}$$ **Equation 2**

As the results from the stock turbocharger were not satisfactory, the subsequent iterations utilized customized turbochargers. A customized turbocharger manufacturing company provided input to help with the development of a turbocharger for optimal use in HCCI mode of operation, determining the optimal turbine housing and compressor housing with compressor impeller and turbine shaft by iterating the system configurations. Table 6 summarizes the results for each of the studied turbocharger arrangements. Figure 4 illustrates some of the turbocharger iterations.

Table 6 - Turbocharger Iteration Summary

Turbocharger Iteration	Air Flow (kg/hr)	Boost (kPa)*	Pressure Ratio (P_r) **	Back Pressure (P_b)
1	227.8	110	1.12	1.43
2	253.6	106	1.15	1.29
3	245.2	129	1.31	1.44
4	269.2	143	1.44	1.70
5	276.5	151	1.53	1.84
6	302.1	142	1.49	1.85
7	286.0	131	1.44	1.68
8	335.9	148	1.61	1.82

* Based on MAP **Based across turbo

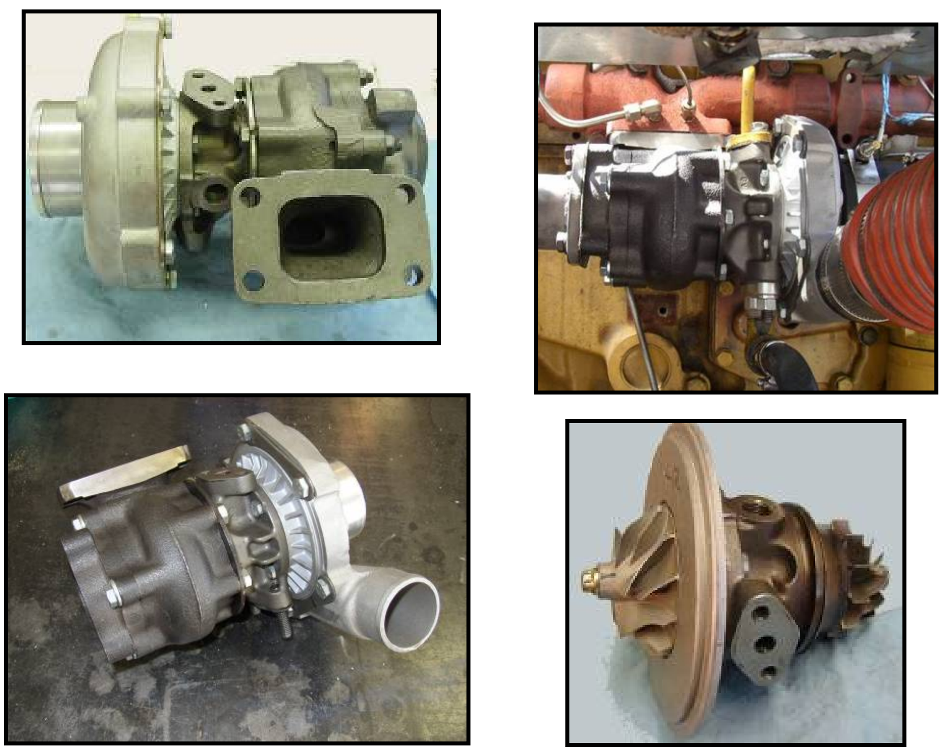


Figure 4 – Turbocharger Iterations

Increased boost pressure allows more fuel to be present per combustion stoke due to an increase in the density of the intake charge. Increased air flow is a direct effect of having a higher boost pressure. Increasing these parameters leads to higher power output. It was determined that for optimal power output, the engine would need to be operating with a boost of 200 kPa passing about 450 kilograms per hour of air. Working towards this goal, a boost pressure of about 150 kPa moving about 335 kilograms per hour of air has been achieved.

3.1.2 Instrumentation and Control

A customized control system was developed to monitor and control engine operation. A host PC/laptop provides a platform for the feedback control system and processes the auxiliary measurements for diagnostics during system testing (Figure 5). Components for control and measurement include thermocouples, mass flow meters, a manifold absolute pressure (MAP) sensor, watt transducer, heaters, electrically actuated valves, and data acquisition modules. The system also includes a soft start.

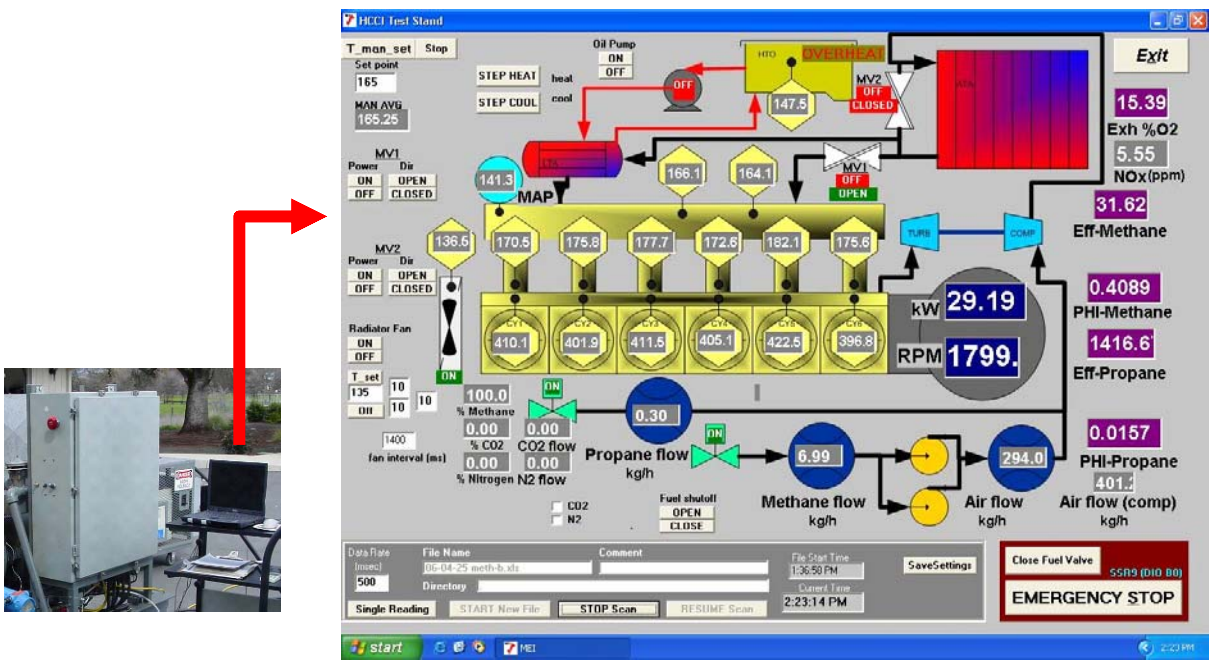


Figure 5 – Control System User Interface

The control system can be broken down into the thermal control system and the data acquisition system. The main components of the thermal control system are the thermocouple inputs, the relays and electrically actuated butterfly valves. The data acquisition system includes thermocouples, mass flow meters, MAP sensor, tachometer, and watt transducer. In addition, a safety shut down sequence is executed when the conditions are such that the engine may be potentially damaged.

Soft Start

A Magnetek soft start (part number RVS-DN) is designed for use with standard three-phase, three-wire, squirrel cage induction motors. It provides a reliable method of reducing the "in rush current" (which can be 9 times the steady state full power current rating of the motor.) and torque during motor start up. The RVS-DN starts the electric motor/generator by supplying a slowly increasing voltage, providing a "soft start" up and smooth electrical acceleration, while drawing the minimum current necessary to ramp up the electric motor/generator the synchronous speed of 1800 RPM.

Safety System

The safety system is intended to prevent damage to the engine or hazardous operation of the system, both when supervised by an operator and when running unattended. Events that would trigger a shutdown include: manual emergency stop (E-stop) engaged, host PC crash, overheating, loss of oil pressure, and RPM runaway.

Thermal Control

The thermal control system can be described as performing two main functions: 1) control the bulk inlet manifold temperature and 2) control the individual temperature of the cylinders (the ICTC manifold). At the beginning of a run, the user inputs the desired bulk manifold set temperature, and the individual targets for each cylinder. Figure 6 illustrates the main areas of the thermal control system.

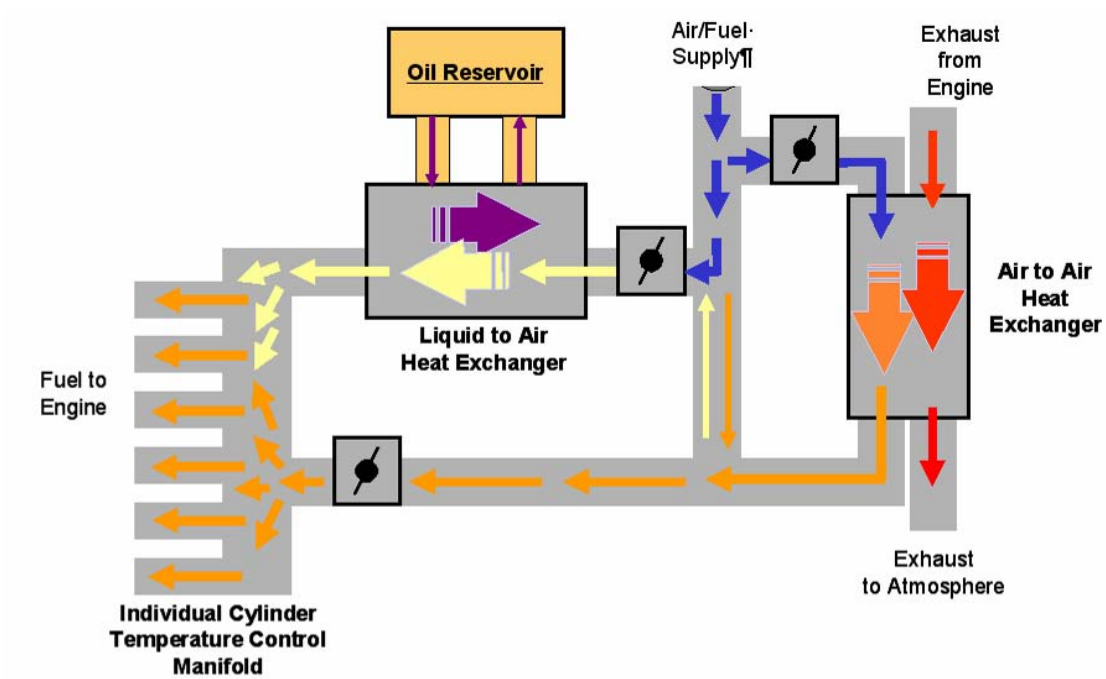


Figure 6 – Thermal Control Schematic

The control of the bulk temperature is done via the butterfly valve in the intake line. Adjustments cause more or less flow to be directed to the heat exchanger, in effect controlling the temperature. The control of the individual cylinder is done via independent heaters. The control algorithm adjusts the duty cycle of the individual heaters as necessary, maintaining the target temperatures.

Equivalence Ratio Control

The Equivalence Ratio (PHI) is defined by Equation 3:

Equivalence Ratio $$\phi = \frac{(A/F)_s}{(A/F)}$$ **Equation 3**

Where $(A/F)_s$ is defined as the ratio between Air to Fuel ratio at stoichiometric combustion and (A/F) is the actual Air to Fuel ratio of the engine.

During operation, equivalence ratio is determined by the mass flow of both fuel and air, being computed, logged and displayed real-time by the control system. The fuel control system allows for automatic adjustment of the flow rates. The energy content in the LFG mixture is entered into the control system, which in turn determines the magnitude of the fuel rate adjustment. During natural gas bench testing, the equivalence ratio was set manually with a ball valve. For field testing, a proportional control valve was utilized to control the equivalence ratio. A block diagram of the equivalence ratio control scheme is shown in Figure 7. If PHI is within the acceptable range, no action is taken. If ϕ is too low, the fuel flow rate is be increased, if PHI is too high, the fuel flow rate is decreased. A fine control was implemented by actuating the valve that controls the fuel flow.

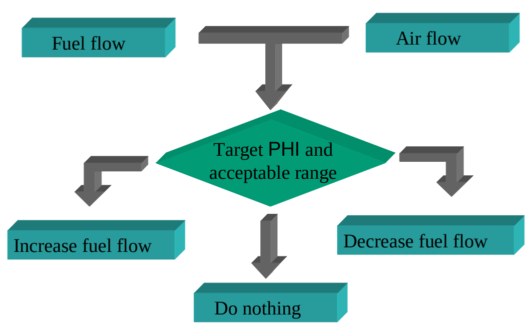


Figure 7 - Air/Fuel Control System

3.2 Engine Retrofitting

The development of the HCCI genset required MEI to perform modifications to a stock CAT 3116 truck engine. The HCCI generator system consists of the following components: a modified fixed displacement reciprocating engine, an electric generator, thermal conditioning system for air-fuel (A/F) mixing and thermal management, instrumentation and actuators, and an automated control system. MEI started with a stock CAT 3116 truck engine with an SAE 14 bell housing shown in Figure 8. It was coupled to an induction generator and appropriate intake ducting was installed as depicted in Figure 9. The thermal conditioning system (Figure 10) hardware comprised of the air to air heat exchanger (ATA), liquid to air heat exchanger (LTA) and the Individual cylinder temperature control (ICTC) manifold were installed. The genset was retro fitted with a custom turbocharger shown in Figure 11. Appropriate control valves and instrumentation was installed (Figure 12). The HCCI genset was install as shown in Figure 13.

Figure 8 – Stock CAT 3116 Truck Engine

Figure 9 – Engine Coupled to Generator

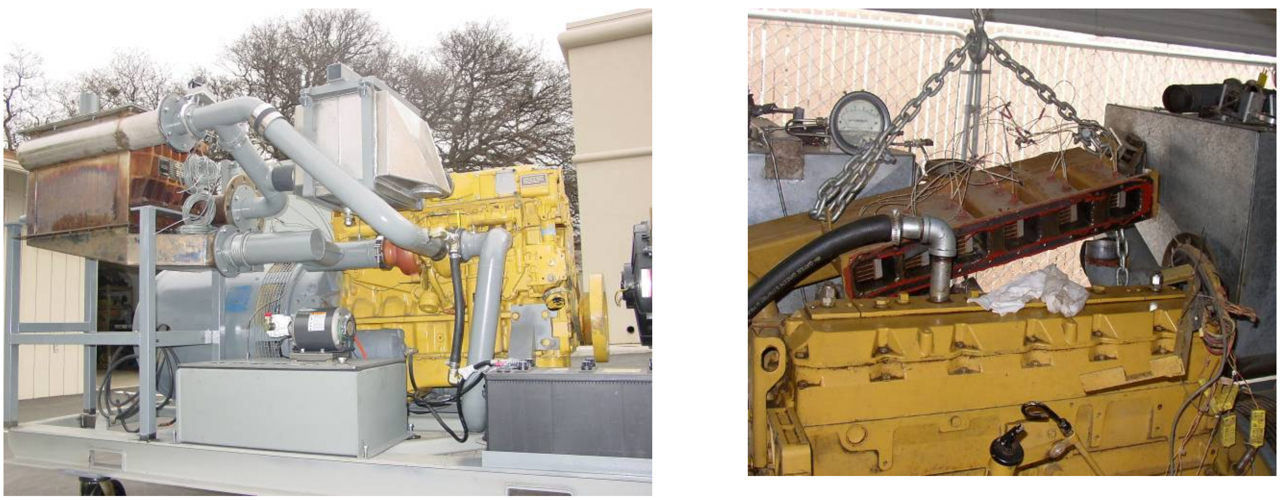


Figure 10 – Thermal Conditioning System –ATA &LTA heat exchangers and ICTC Manifold

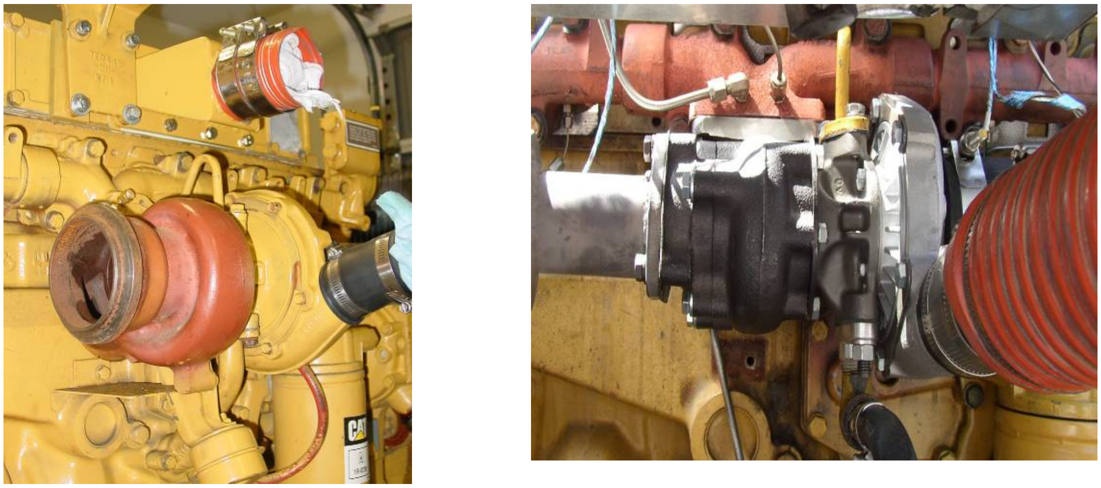


Figure 11 –Turbocharger-Stock (left)/HCCI Hybrid(right)

Figure 12 – Appropriate Control Valves and Instrumentation Installed

Figure 13 – Genset Operating on LFG

3.3 Baseline Testing with Natural Gas

3.3.1 Overview

The operation of the HCCI engine/genset system was evaluated by inspection and testing. Evaluation included safety and functional setup tests as well as characterization and optimization performance tests. The safety and functional tests ensured that the control system, specifically safety shutdown, was sound. The characterization tests helped to provide baseline values for generator efficiency and NO_X emissions at a given equivalence ratio. The optimization tests allowed for improvement upon the generator efficiency and NO_X emission baselines established in the characterization tests. As the program evolved, modifications to the test plan were made. As deemed necessary to further investigate individual characteristics of HCCI operation, the original Bench Test Plan (task 2.2) was improved to accommodate the new testing requirements. Table 7 lists the individual tests that were carried out on the HCCI engine/genset system for baseline testing with natural gas. For detailed description of these tests, refer to the test plan.

Table 7 – Baseline Test Plan Overview

6.1 Test Stand Control System Tests
6.1.1 Host PC Communication Test
6.1.2 HCCI Control System Communication Test
6.1.3 Mass Flow Meter Characterization Test
6.2 Safety Shutdown Functional Tests
6.2.1 Manual Kill Button Test
6.2.2 Host PC Shutdown Test
6.2.3 Control System Software Shutdown Test
6.2.4 Overheating Shutdown Functional Test
6.2.5 HTO Temperature Shutdown Functional Test
6.2.6 RPM Runaway Shutdown Functional Test
6.3 Startup Sequence Characterization Tests
6.3.1 Startup Sequence Validation Test (Propane)
6.3.2 LTA to ATA Transition Test (Propane)
6.3.3 Startup Sequence Validation Test (Natural Gas)
6.4 Steady State Optimization Test
6.4.1 Steady State Operation Validation/Optimization
6.5 Simulated LFG Performance Tests
6.5.1 Startup Sequence Validation Test (Simulated LFG)
6.5.2 LTA to ATA Transition Test (Simulated LFG)
6.5.3 Steady State Operation Validation/Optimization (Simulated LFG)
6.6 Testing with Boost
6.6.1 Startup Sequence Validation Test with Boost
6.6.2 Equivalence Ratio -Temperature Characterization with Boost
6.6.3 Steady State Operation Optimization with Boost

3.3.2 Natural Gas Testing Results

As indicated in the bench test plan, testing consisted of verification of the control electronics and operation of the engine/genset in HCCI mode. After confirming that the system was safe to operate, running the engine/genset in HCCI mode commenced using propane as fuel. Propane as a fuel source led to an understanding of how the engine/genset responded thermally. Natural gas was then utilized as fuel for optimization of the engine output. The project objectives were used as a target for engine output optimization with natural gas. The following sections summarize the bench testing results for the testing categories 6.1 through 6.4 and 6.6. A log of the data files collected is contained in the test report (Baseline Testing with Natural Gas). MEI successfully operated the HCCI genset for 22 months using Natural Gas for a total of 370 hours. Figure 14 shows the cumulative and monthly operation time.

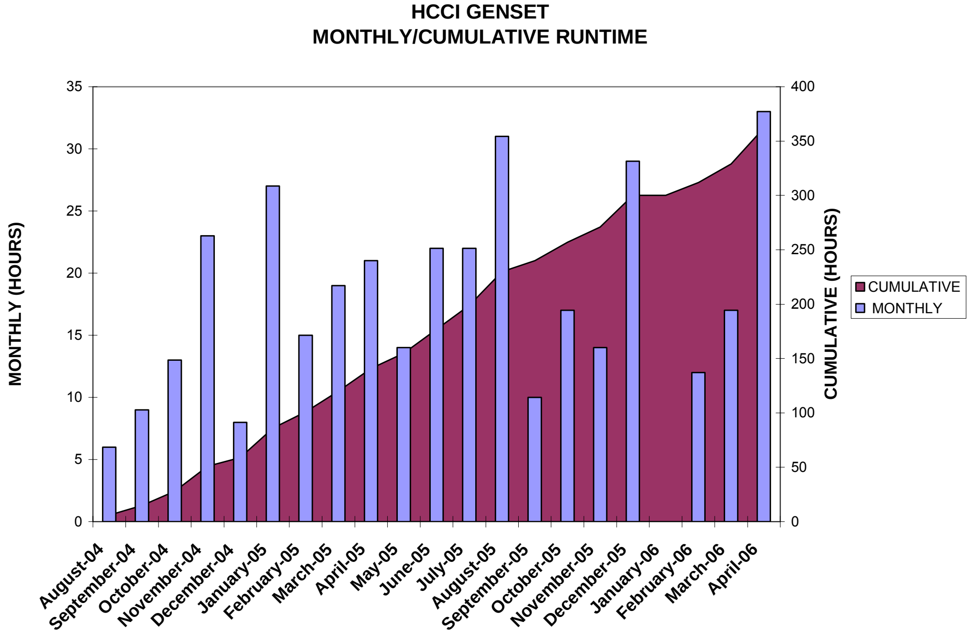


Figure 14 - Engine Operation by Month and Total

Table 8 – Individual Test Results

Result	Specific Test
	6.1 Test Stand Control System Tests
VERIFIED	6.1.1 Host PC Communication Test
VERIFIED	6.1.2 HCCI Control System Communication Test
VERIFIED	6.1.3 Mass Flow Meter Characterization Test
	6.2 Safety Shutdown Functional Tests
VERIFIED	6.2.1 Manual Kill Button Test
VERIFIED	6.2.2 Host PC Shutdown Test
VERIFIED	6.2.3 Control System Software Shutdown Test
VERIFIED	6.2.4 Overheating Shutdown Functional Test
VERIFIED	6.2.5 HTO Temperature Shutdown Functional Test
VERIFIED	6.2.6 RPM Runaway Shutdown Functional Test
	6.3 Startup Sequence Characterization Tests
VERIFIED	6.3.1 Startup Sequence Validation Test (Propane)
VERIFIED	6.3.2 LTA to ATA Transition Test (Propane)
VERIFIED	6.3.3 Startup Sequence Validation Test (Natural Gas)
	6.4 Steady State Optimization Test
VERIFIED	6.4.1 Steady State Operation Validation/Optimization
	6.5 Simulated LFG Performance Tests
TASK 2.4	6.5.1 Startup Sequence Validation Test (Simulated LFG)
TASK 2.4	6.5.2 LTA to ATA Transition Test (Simulated LFG)
TASK 2.4	6.5.3 Steady State Operation Validation/Optimization (Simulated LFG)
	6.6 Testing with Boost
VERIFIED	6.6.1 Startup Sequence Validation Test with Boost
VERIFIED	6.6.2 Equivalence Ratio -Temperature Characterization with Boost
VERIFIED	6.6.3 Steady State Operation Optimization with Boost

3.3.2.1 Control System Tests

Tests were conducted to confirm system communications and validate the system's fundamental logic. It was established that the motor valves, HTO pump, radiator set point, bulk manifold set point and fuel shutoff valves functioned properly, and that the control system was able to generate and log data. Conversion factors for propane and methane flow meters were verified.

3.3.2.2 Safety Test Results

The safety system is intended to prevent damage to the engine or hazardous operation of the system, both when supervised by an operator and when running unattended. Table 9 lists the parameters which trigger a shutdown action. Events that would trigger a shutdown include: manual emergency stop (E-stop) engaged, host PC crash, overheating, loss of oil pressure, and RPM runaway.

The engine/genset cannot operate without fuel. All safety shutdown tests resulted in the shutdown of the fuel supply to the engine, insuring operator and system safety. Figure 15 depicts a typical plot of fuel flow when a shutdown event is triggered. System safety was confirmed by recording the fuel flow rate when a safety shutdown parameter was prompted. Shutdown parameters are listed in Table 9. Note that the fuel flow rate drops to zero when an event is triggered.

Table 9 - Shutdown Parameters

Condition	Parameter	Action
E-stop switch	operator input	Close Fuel Valve
Host PC	computer shutdown	Close Fuel Valve
Engine Coolant Overheating	>160^{o}C	Close Fuel Valve
HTO Reservoir Overheating	> 180^{o}C	Disconnect Heater Power
Engine Manifold Overheating	>250^{o}C	Close Fuel Valve
Loss of Oil Pressure	< 10psi	Close Fuel Valve
RPM Runaway	>2000 RPM	Close Fuel Valve

The reset switch must be activated for any system to be turned on (pumps, heaters, starter, fuel, solenoid, etc.). If the E-stop switch is activated the fuel solenoid closes immediately and the master power is shut off. When there is no signal from the Host PC, the fuel solenoid is kept closed, therefore, in the event of power loss/shutdown of the host PC no fuel flows. The tachometer output protects the system against both over speed and under speed. If the engine speed exceeds the maximum desired value, the fuel solenoid is tripped. If the engine speed remains below the minimum set speed for more than 1 minute (i.e., the engine has stalled), the fuel solenoid closes immediately. If the oil pressure falls below the minimum set point, the coolant temperature exceeds the maximum coolant temperature, or the oil exceeds the maximum temperature, the fuel solenoid closes.

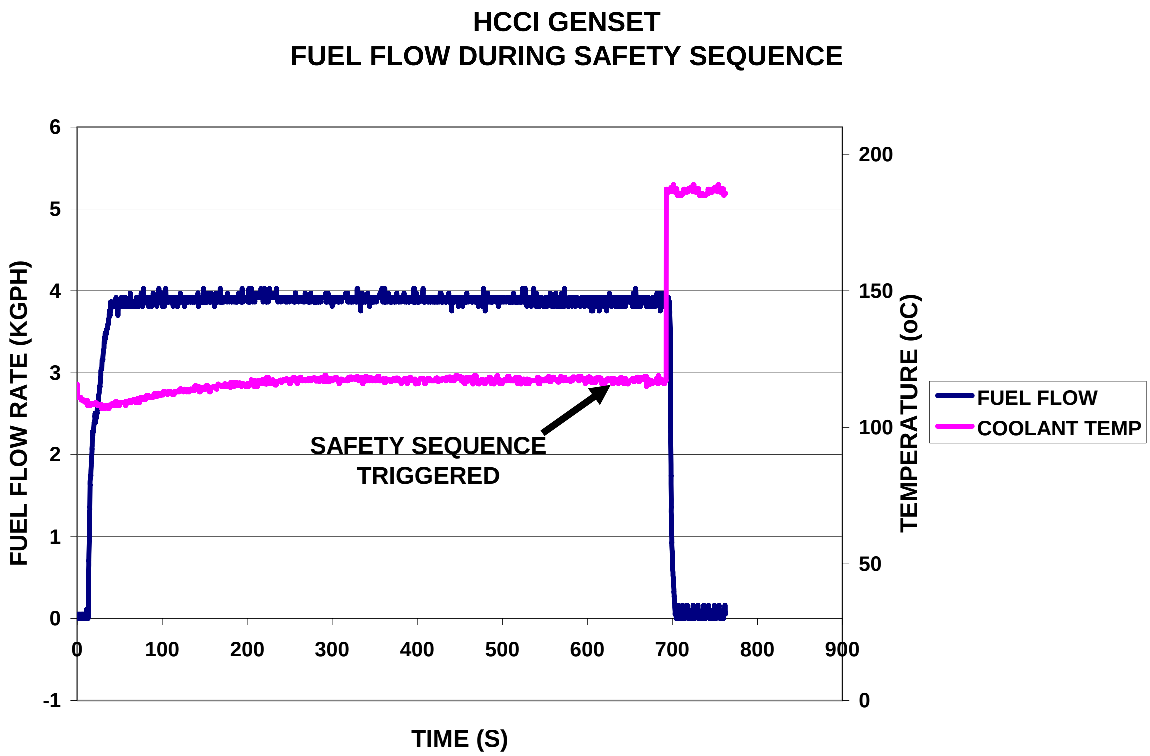


Figure 15 - Resulting Fuel Flow During a Safety Shutdown

3.3.2.3 Start Up Test Results

Using propane for fuel, the startup sequence has been verified. The outcome of the start up testing was the development of a start up procedure. The engine is capable of making the LTA to ATA heat exchanger transition as well as the propane to natural gas transition. Figure 16 depicts the typical bulk inlet manifold temperature during the startup process. During startup, the engine operates on propane fuel for approximately 15 minutes. The LTA heat exchanger provides a bulk manifold set temperature of about 130 Celsius (location “1” on plot). During this time, the ATA heat exchanger is being heated from the hot exhaust gases. As the LTA to ATA heat exchanger transition takes place, a perturbation in inlet temperature is observed (location “2” on plot). This is due to the positioning of butterfly valves which allow the intake charge to bypass the LTA heat exchanger. The change in bulk manifold temperature does not cause the engine to misfire.

After making the ATA to LTA transition, the bulk manifold temperature is held at approximately 110 Celsius for about 10 minutes while the engine operates steadily on propane as fuel (location “3” on plot). Next, natural gas is introduced as fuel while the propane fuel is shut off. During the propane to natural gas transition, the bulk manifold temperature set temperature is changed to 195 Celsius. Natural gas is slowly added to the intake charge and propane flow is slowly decreased until no propane is flowing (location “4” on plot). Finally the engine is operating on natural gas (location “5” on plot).

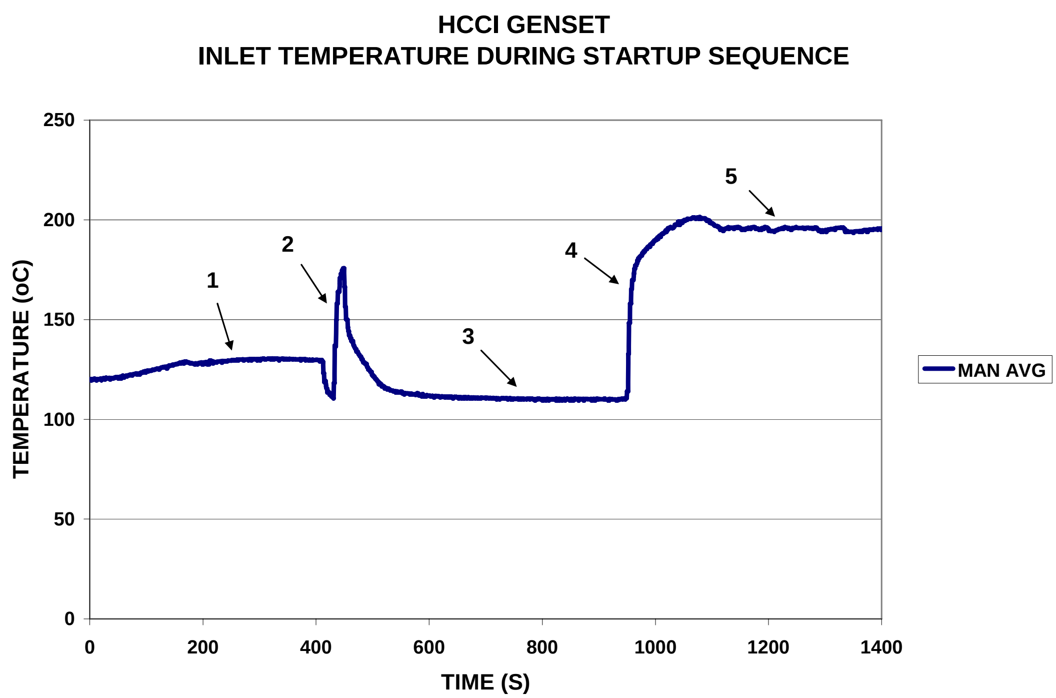


Figure 16 - Bulk Inlet Manifold Temperature During Startup

This testing sequence was also used to determine to establish engine inlet temperatures at which propane or natural gas will auto ignite. Based on the engine efficiency, it was determined that the optimal inlet temperature for propane (TP) to auto ignite is 110 degrees Celsius. It was determined that the optimal inlet temperature for natural gas (TM) to auto ignite is 165 degrees Celsius.

3.3.3 Genset Energy Balance

The HCCI genset is comprised of a reciprocating engine coupled to an electrical generator with a modified intake system. The main components of the system include: engine, radiator and generator. The components of the subsystem include: HTO oil reservoir, LTA heat exchanger, ATA heat exchanger and turbocharger. A simplified schematic of the HCCI genset is shown in Figure 17 illustrates the power distribution points of the system. Table 10 defines and summarizes typical values for the power distribution points.

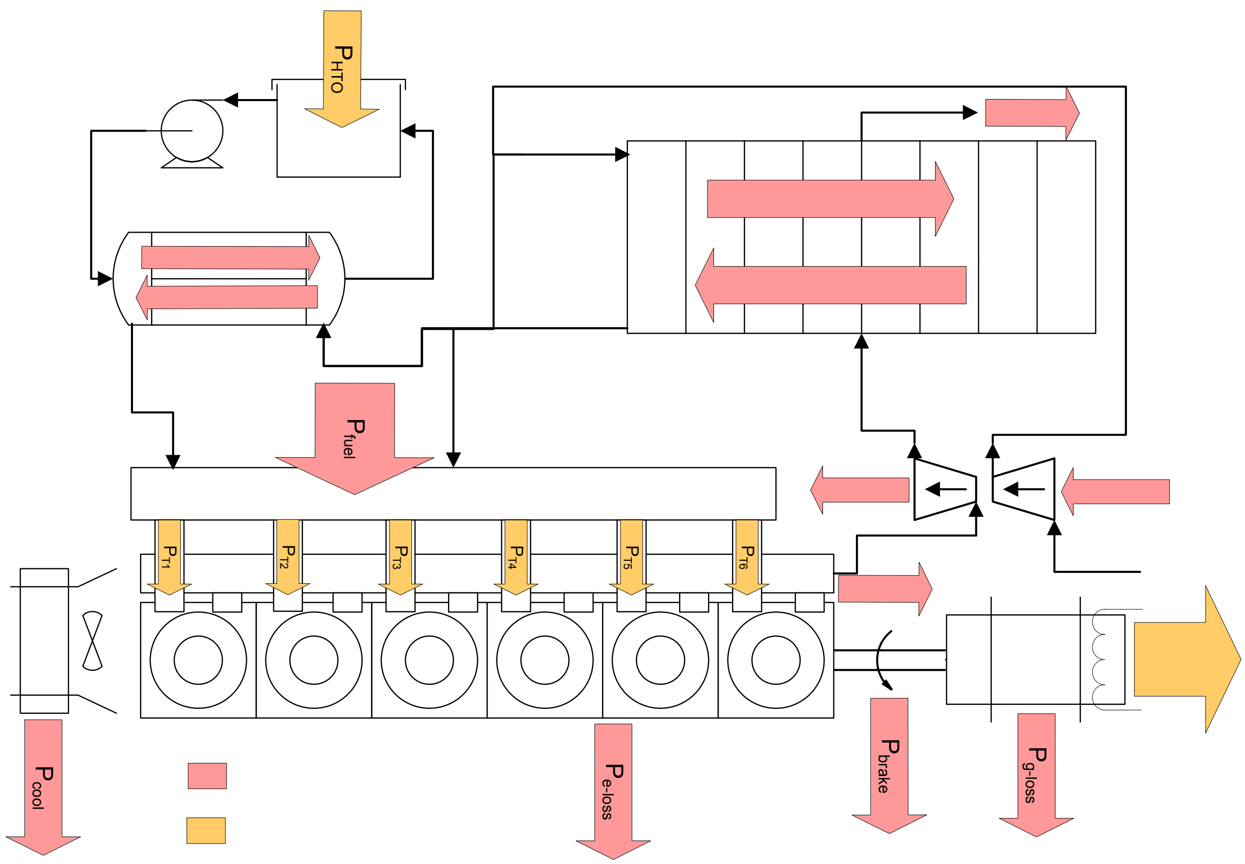


Figure 17 - HCCI Genset Power Distribution Points

Table 10 - Definitions and Typical Values for Power Distribution Points

Symbol	Definition	Value (kW)
P_{HTO}:	Electrical power input to HTO during startup	**12.0**
$P_{HTO\text{-}LTA}$:	Power input from HTO during startup	**11.5**
$P_{int\text{-}LTA}$:	Power added to intake stream during startup	**10.0**
$P_{T1\ to\ T6}$:	Electrical power input to trim heaters	**0.0 to 0.4**
P_{fuel}:	Power from combustion of fuel	**85.0**
$P_{e\text{-}exh}$:	Power loss from evacuated exhaust gases pre-turbo and ATA	**30.0**
$P_{e\text{-}loss}$:	Engine power losses	**5.0**
P_{cool}:	Power rejected by engine coolant	**25.0 to 28.0**
$P_{exh\text{-}ATA}$:	Power recovered from exhaust stream	**17.0**
$P_{int\text{-}ATA}$:	Power added to intake stream during steady state operation	**10.0**
P_{exh}:	Power loss from escaping exhaust gases	**6.5**
P_{turb}:	Power recovered from the turbine side of the turbocharger	**6.5**
P_{comp}:	Power added to intake stream from turbocharger compressor	**6.0**
P_{brake}:	Brake power at the engine's crankshaft	**27.0 to 30.0**
$P_{g\text{-}loss}$:	Power losses associated with the generator	**2.0**
P_{gen}:	Electrical power output	**25.0 to 27.0**

The HCCI intake charge requires about 10.0 kW of heating achieve to an ideal intake temperature for combustion to occur. The modified intake supplies the required heat to achieve inlet temperature. This heating is supplied by electrical power during startup and recuperated exhaust heat during steady state operation.

The LTA sub-system is comprised of the HTO reservoir, oil pump and LTA heat exchanger. The HTO requires 12.0 kW (six 2.0 kW, 220V AC electric heaters) of electrical energy (P_{HTO}) for a duration of 1 hour to warm the sub-system. The HTO is pumped through the LTA heat exchanger warming ($P_{HTO\text{-}LTA}$) the heat exchanger on the liquid or oil side. The incoming air on the air side of the heat exchanger is then warmed ($P_{int\text{-}LTA}$) by the heat exchanger. Testing has determined that the LTA sub-system is approximately 65% effective. About 650 Watts of power heats the intake charge per 1.0 kW of electrical heating at a mass flow rate of about 280 kgph. The electrical trim heaters in the ICTC manifold provide up to 400 W ($P_{T1\ to\ T6}$) of additional heating per cylinder.

The BTU value of the natural gas delivered to MEI's testing facility changed daily. The daily value was accounted for in all testing. For engineering computations, the daily BTU value was converted to a lower heating value of in kilojoules per kilogram. The average lower heating value was 47,200 kJ/kg. Operating at an equivalence ratio of 0.33 and an inlet pressure of 1.5

atm, the mass flow of natural gas is about 6.5 kgph. The combustion of natural gas at this flow rate releases approximately 85.0 kW of power (P_{fuel}).

Not all of this power is converted directly into electrical power. About 30.0 kW of this energy (P_{e-exh}) is evacuated as hot exhaust gases. Other engine power losses account for about 5.0% or 5.0 kW of the power from the fuel. These losses (P_{e-loss}) include: radiation, lubrication system and other small losses.

A large part of this heat is lost to the piston chamber walls. To prevent the piston walls from becoming too hot, the cooling system is removes heat through the circulation of engine coolant. The engine cooling system is comprised of water pump, radiator and fans. At 1800 RPM, the water pump has a flow rate is approximately 50.0 kgpm. Operating with a 70% ethylene glycol to 30% water coolant/water mixture, the cooling system is capable of removing from 25.0 to 28.0 kW (P_{cool}) depending on fan speed.

At a mass flow rate of about 320 kgph, about 17.0 kW of power ($P_{exh-ATA}$) is recovered from the exhaust stream providing the required 10.0 kW of power ($P_{int-ATA}$) to the intake stream. About 6.5 kW is released to the atmosphere (P_{exh}) in the exhaust gases leaving the ATA. At steady state the ATA is approximately 65% effective.

The turbocharger also recovers some of the power loss from the evacuated exhaust gases. The turbine side of the turbocharger converts about 6.5 kW exhaust heat into mechanical energy to drive the compressor side of the turbocharger. The compressor side of the turbocharger adds about 6.0 kW of heat to the intake charge (P_{comp}). See steady state operation results for turbocharger optimization.

About 27.0 to 30.0 kW of the power available from the fuel remains at the engine crankshaft defined as engine brake power (P_{brake}). The electric generator is very efficient. The nameplate efficiency rating on the Century 150kW motor is 93%. Power loss thru the generator (P_{g-loss}) is assumed to be about 7% or 2.0 kW of the brake power at the engine crankshaft. Finally, the genset outputs from 24.0 to 27.0 kW of electrical power (P_{gen}).

During steady operation, the ATA heat exchanger recuperates more than the required 10.0 kW of heating. To maintain a desired intake temperature, a portion of the intake charge bypasses the ATA. A motorized butterfly valve in the intake system prior to the ATA is “dithered” to control bulk manifold inlet temperature. A control algorithm with programmable dead band and response time has allowed for a bulk inlet temperature to be controlled to within 1.0 degree Celsius.

3.3.4 Steady State Operation Results

After validating the system start-up procedure, MEI continued to optimize system outputs working towards the program goals. Optimization steps included:

- Establishing a baseline system efficiency
- Increasing power output through the development the turbocharger
- Optimizing the intake system
- Determining the inlet conditions and equivalence ratio that optimized NOx emissions in relationship to efficiency

System efficiency is defined as the fuel to electricity power ratio for the system. It is computed using Equation 4.

System Efficiency $$\eta = \frac{(P_{gen})(3600)}{(m_{fuel})(LHV_{fuel})}$$ **Equation 4**

Where (P_{gen}) is the electrical power output in kW, (m_{fuel}) is the mass flow of the fuel in kilograms per hour and (LHV_{fuel}) is the lower heating value of the fuel in kilojoules per kilogram.

3.3.4.1 System Efficiency and Power Output

After about 80 hours of testing, MEI successfully achieved steady operation in HCCI mode while operating on natural gas. It required about 60 minutes to achieve these conditions. Efficiency and power data obtained during this time was used to improve the system. Modifications to the system has allowed for improved outputs; working towards the project goals. Modifications to the engine/genset were developed around the intake system and engine block/pistons. The engine/genset underwent five major modifications. These five engine configurations with their corresponding maximum efficiencies and power outputs are summarized in Table 11.

Table 11 - Engine/Genset Configuration and Output Summary

Configuration	Description	System Efficiency (%)	Power (kW)
A	Original configuration	**18.0**	**15.3**
B	Original engine with modified intake simple	**19.4**	**18.2**
C	Original engine with ICTC intake	**23.1**	**21.5**
D	Original engine with modified inlet to ICTC	**24.2**	**22.2**
E	Re-built engine with ICTC intake (Current)	**32.6**	**26.9**

The original engine configuration (configuration “A”) was important stepping stone to the current design. It validated that the system was capable of operating in HCCI mode with natural gas as a fuel source. It also served as a test platform for the electronics and instrumentation. The best efficiency was found to be 18.0% while producing about 15 kW of electrical power.

A temperature difference along the intake manifold was noted. To combat this temperature difference, electrical heaters were added to the front and rear of the intake manifold (configuration “B”). With these heaters, MEI was able to affect the inlet temperature to cylinder #1 and #2 or cylinders #3 through #6. Inlet temperature variation allowed for more optimal timing of the combustion. While only a slight increase in efficiency (19.0%) was recorded, a significant increase in power output (18.0 kW) was achieved. This led to an understanding that the key to optimizing the system output was developing the capability to independently affect the inlet temperature to each individual cylinder.

Improved engine performance from the addition of front and rear trim heaters, led to the development of an individual cylinder temperature control (ICTC) manifold. The inclusion of a turbocharger to the intake system as well as routing the heated intake charge through a six-way manifold (configuration “C”), allowed an improvement in efficiency to 23.0% while producing 21.0 kW of electrical power. The remaining tests were conducted with a turbocharger.

The ICTC manifold proved to be a valuable addition to the engine/genset; however; a minor modification to the inlet to the ICTC manifold was need to combat a temperature gradient which had developed from the inlet to the ICTC manifold at cylinder #6 towards cylinder #1. To provide a more uniform bulk inlet temperature, the inlet to the ICTC manifold was re-routed to enter the middle of the ICTC manifold (configuration “D”). This modification improved the efficiency to 24.0% while producing 22.0 kW of electrical power.

Potential sources for the lower than expected efficiency were identified as the following: non-optimal ignition timing of all six cylinders, lower than expected compression due to leakage around piston rings and higher than expected friction in the engine. MEI replaced the engine block with a new short block (configuration “E”) consisting of new pistons, rings, and crank shaft. Re-building the engine/genset ensured that we do not reach potential incorrect conclusions based unique problems with the original engine block. After this modification to the genset, the efficiency numbers were 5% to 10% improved. The engine currently is capable of achieving 32.5% efficiency and producing about 27.0 kW.

3.3.4.2 System Optimization and Emissions Output for Natural Gas

Without the utilization of a turbocharger, the HCCI engine/genset was unable to sustain steady operation. Working through several turbocharger iterations has afforded MEI to optimize the power and efficiency output while mapping the emissions output of the HCCI engine/genset. The effect of an optimized turbocharger has been higher boost pressure at the engine intake manifold. Figure 18 shows the effect of boost pressure on system efficiency for turbocharger iteration #8.

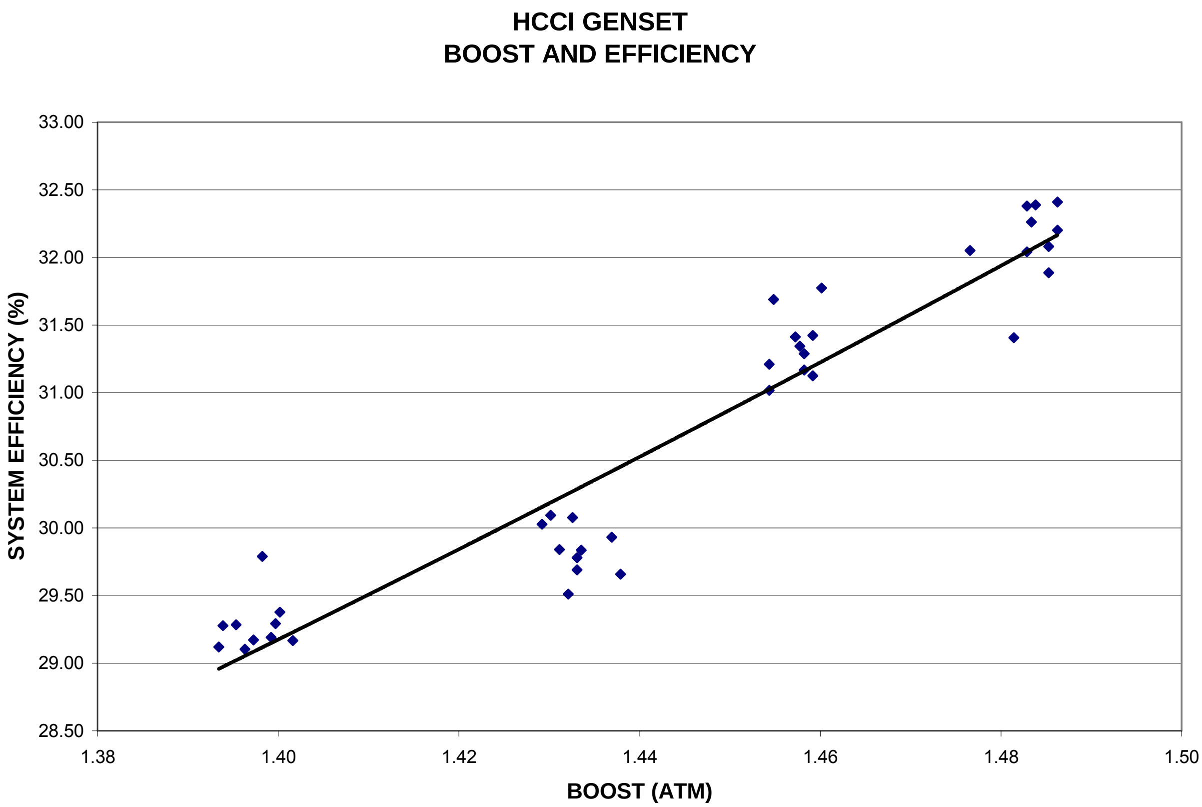


Figure 18 - HCCI Performance – Turbocharger Boost and System efficiency

When turbocharger iteration #8 was operated at about 1.4 bar, a system efficiency of about 29.0% was recorded. When the same turbocharger was operated at about 1.5 bar, the system efficiency was about 32.5%.

All optimization testing was done while the engine was under a 70 kW load being fed by both the grid and the HCCI genset. The peak fuel to electricity efficiency was about 33.0% while producing about 27.0 kW of power; however under these operating conditions the NO_x emissions did not meet program goals. By lowering the equivalence ratio and increasing the inlet temperature MEI was able to achieve a peak fuel-to-electricity efficiency of about 31.0% while producing 24.0 kW of power and generating less than 4.0 ppm NOx emissions. Table 12 summarizes the operating conditions which produced these results.

Table 12 - HCCI Performance –Peak Efficiency and Emissions Level

INLET CONDITION			OUTPUT		
EQUIV. RATIO	INTAKE MANIFOLD TEMP(oC)	MAP (BAR)	POWER OUTPUT (kW)	SYSTEM EFFICIENCY	NOx LEVEL (ppm) - (lb/MW-hr)
0.36	160	1.45	26.9	32.6%	9.2 (0.17)
0.33	165	1.46	23.9	30.6%	3.6 (0.06)

*Corrected for dry 15.0% Oxygen

Figure 19 shows the NO_x emissions as a function of equivalence ratio. As anticipated, the NO_x emission levels decrease at lower equivalence ratios.

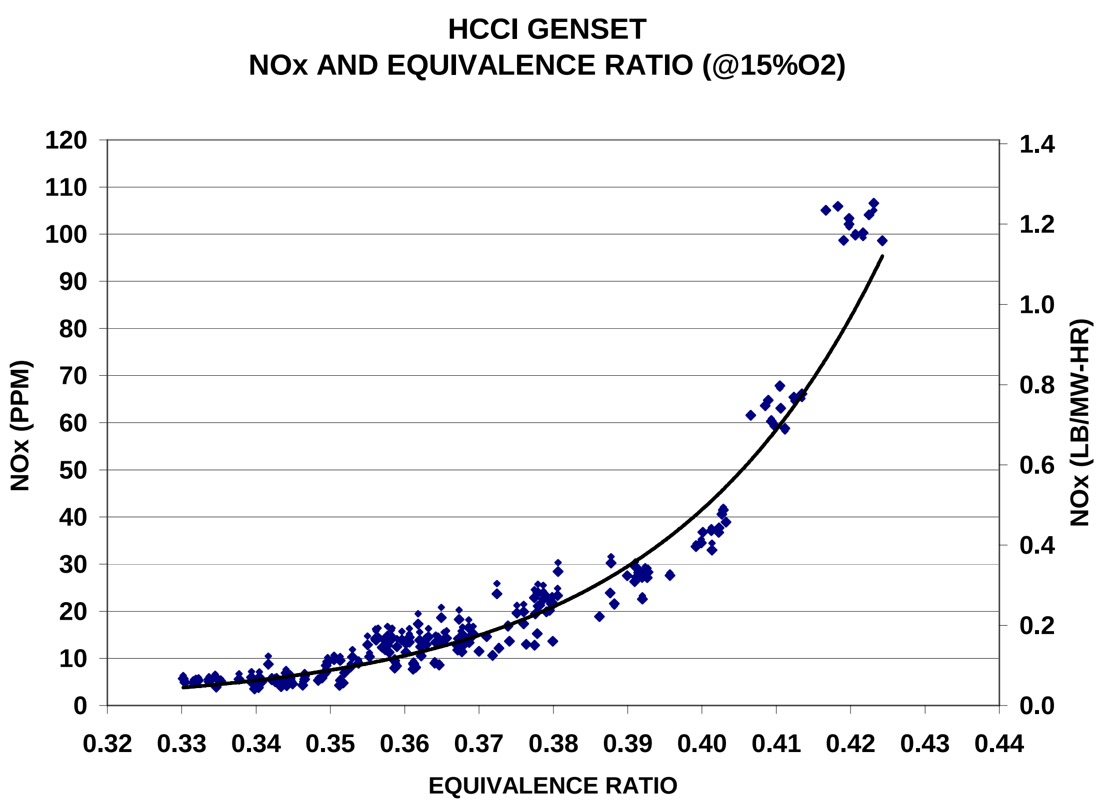


Figure 19 - HCCI Performance –NO_x Emission Levels and Equivalence Ratio

From an emissions standpoint, the HCCI genset produces significantly less NOx without the utilization of after treatments. Table 13 compares the LFG HCCI genset to both the program goals and a conventional lean burn natural gas engines.

Table 13 – HCCI Engine Comparison

	CUMMINS*	WAUKESHA**	LFG HCCI GENSET	PROGRAM GOALS
BRAKE THERMAL EFFICIENCY	30-35%	30-35%	35%	> 35%
NOx EMISSIONS				
NO AFTER TREATMENT	175 ppm (2.5 lb/MWh)	410 ppm (5.9 lb/MWh)	3.6 ppm (0.06 lb/MWh)	< 5.0 ppm (0.07 lb/MWh)
SELECTIVE CATALYTIC REDUCTION	30 ppm (.45 lb/MWh)			
LOW NOx MODE		205 ppm (2.9 lb/MWh)		
TURBO BOOST	2.0 atm	2.0 atm	1.5 atm	
EQUIV. RATIO	0.70 to 0.80	0.70 to 0.80	0.30 to 0.34	0.30 to 0.40

*CUMMINS QSK19G Spark ignited 6-Cylinder 19 liter (QSK19G datasheet)
**WAUKESHA H24GL Spark ignited 8-Cylinder 24 liter (H24GL datasheet)

3.4 Baseline Testing with Simulated Landfill Gas

3.4.1 Test Plan Overview

Simulated landfill gas tests are described in the baseline test plan and the test outline is provided in Table 7 in section 3.3.1 of this report.

3.4.2 Simulated Landfill Gas Testing Results

As indicated in the bench test plan, testing consisted of verification of the control electronics and operation of the engine/genset in HCCI mode. As summarized by task 2.3, Bench Testing with Natural Gas, natural gas was utilized as fuel for optimization of the engine output. The project objectives were then used as a target for engine output optimization with simulated landfill gas as a fuel source. A log of the comprehensive data files collected is contained in the test report (Baseline Testing with Simulated Landfill Gas). Table 14 shows the results from the simulated landfill gas testing in section 6.5 of the Bench Test plan. The following sections summarize the bench testing results for this testing.

Table 14 – Individual Test Results

Result	Specific Test
	6.5 Simulated LFG Performance Tests
VERIFIED	6.5.1 Startup Sequence Validation Test (Simulated LFG)
VERIFIED	6.5.2 LTA to ATA Transition Test (Simulated LFG)
VERIFIED	6.5.3 Steady State Operation Validation/Optimization (Simulated LFG)

3.4.2.1 Landfill Gas Composition

Tapping into the existing flaring station at the NRL, a delivery manifold to port the landfill gas over to the HCCI genset was installed. The methane, nitrogen and carbon dioxide concentrations of the LFG from NRL have been monitored weekly for the past several months. The flare flow rate has varied from about 675 CFM to 1000 CFM. The methane concentration ranged from 35% to 60%. The carbon dioxide concentration varied from 25% to 30%. Figure 20 shows the methane, carbon dioxide and nitrogen concentrations for LFG sampling. The gas sampling method used is not capable distinguishing nitrogen from air. For sampling, the balance gas was assumed to be nitrogen. The most recent data has indicated about 40% methane, 30% nitrogen and 30% carbon dioxide. The recorded landfill gas compositions listed in Table 15 indicate that the ratio of methane to carbon dioxide varied from 1.3:1 to 2.4:1 and the ratio of methane to nitrogen varies from 1.1:1 to 4:1.

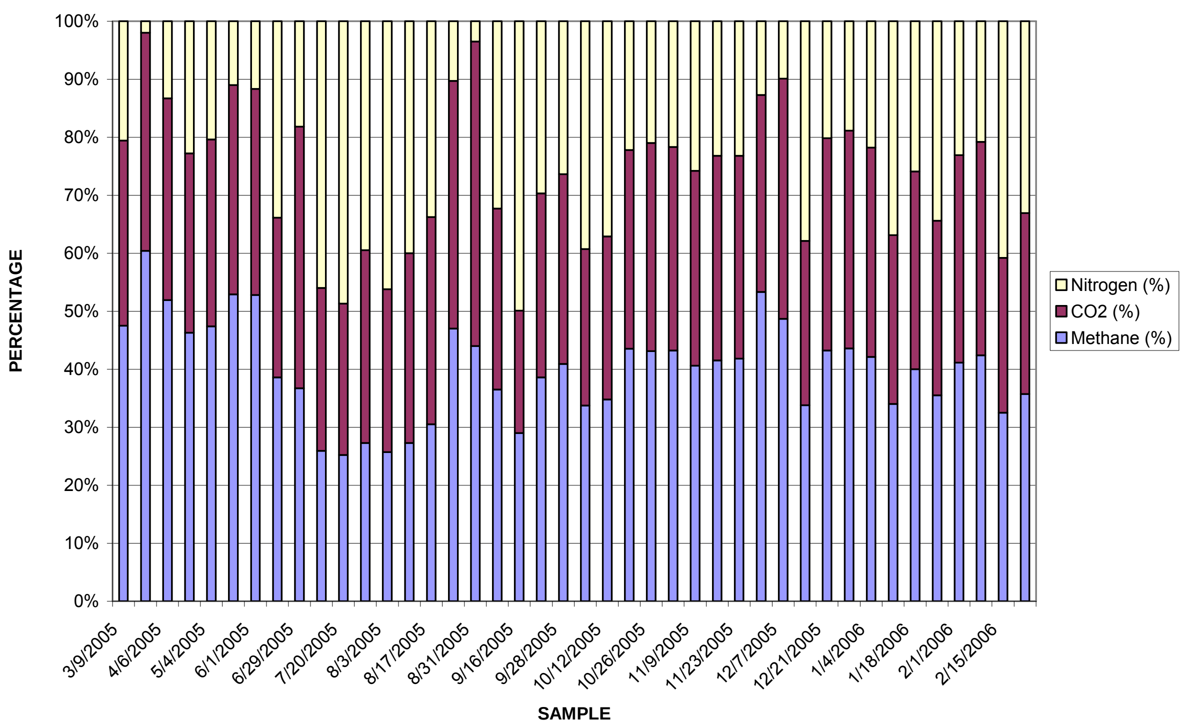


Figure 20 - Respective Methane, Carbon Dioxide and Nitrogen concentrations found in the LFG Samples Pulled from Delivery Manifold at NRL

Table 15 - Measured Landfill Gas Compositions

FUEL	CH_4	CO_2	N_2	(CH_4: CO_2)	(CH_4: N_2)
Most Methane	60	25	15	2.4:1	4:1
Typical	40	30	30	1.3:1	1.3:1
Least Methane	35	25	30	1.4:1	1.1:1

For SLFG testing, MEI used a worse case of scenario for high carbon dioxide concentration and also for high nitrogen concentration in the LFG. Figure 21 depicts an example of how the SLFG fuel mixture was delivered to the engine for SLFG performance testing. Diluent gas ratios for CH_4: CO_2 and CH_4: N_2 of 1.2:1, 1.5:1 and 1.9:1 were tested. The remaining diluting gas was assumed to be air in both cases. While the engine was operated with all of these concentrations, additional optimization testing was performed with the ratios of 1.5:1 methane balance carbon dioxide to meet the project goals for NO_X emissions.

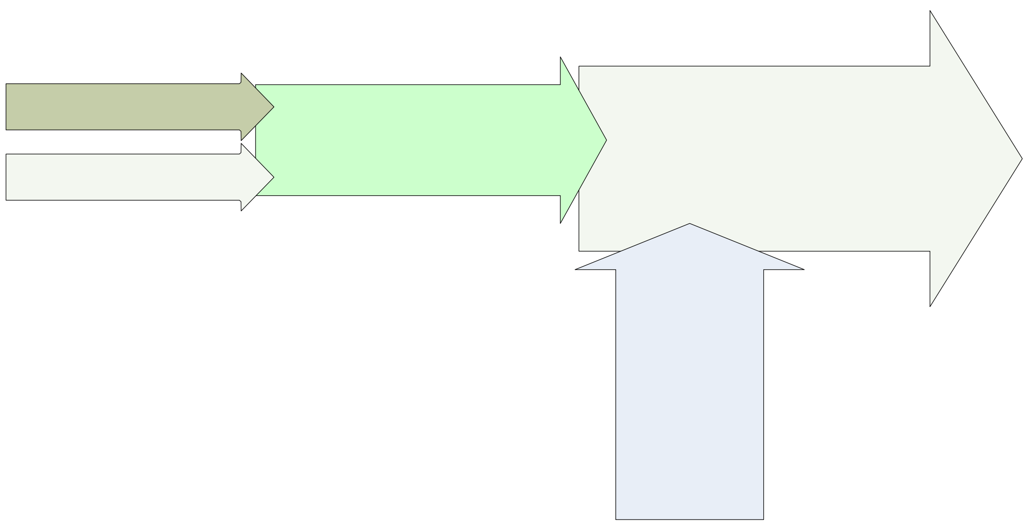


Figure 21 - Simulated Landfill Gas Intake Diagram

3.4.2.2 System Efficiency and Power Output SLFG

After about 80 hours of testing, MEI successfully achieved steady operation in HCCI mode while operating on natural gas. After optimizing the engine for operation on natural gas, MEI developed the most favorable inlet conditions for running on simulated landfill gas. Efficiency and power data obtained during this testing was used to improve the system. Table 11 summarizes the peak efficiency and power output for the optimized carbon dioxide and nitrogen concentrations.

Table 16 - Engine/Genset Peak Output Summary

FUEL	System Efficiency (%)	Power (kW)
NATURAL GAS	**32.6**	**26.9**
METHANE BALANCE CARBON DIOXIDE	**31.6**	**28.9**
METHANE BALANCE NITROGEN	**29.9**	**29.1**

The engine currently is capable of achieving about 31.5% system efficiency or 34.0% brake thermal efficiency and producing about 29.0 kW while operating on simulated landfill gas.

3.4.2.3 System Optimization for SLFG

By lowering the equivalence ratio and increasing the inlet temperature MEI was able to achieve a peak fuel-to-electricity efficiency of about 30.0% while producing about 26.0 kW of power and generating about 5.0 ppm NOx emissions. Table 17 summarizes the operating conditions which produced these results.

Table 17 - HCCI Performance for Simulated Landfill Gas

FUEL	**INLET CONDITION**			**OUTPUT**		
SLFG	**EQUIV. RATIO**	**INTAKE TEMP (oC)**	**MAP (kPa)**	**POWER OUTPUT (kW)**	**BTE (%)**	**NOx LEVEL (ppm)**
1.2:1 (CH_4: CO_2)	0.35	185	146	25.9	32.5%	5.4
1.5:1 (CH_4: CO_2)	0.35	185	142	25.5	30.8%	4.7
1.9:1 (CH_4: CO_2)	0.38	175	143	27.6	32.9%	5.2
1.2:1 (CH_4: N_2)	0.36	170	137	24.4	31.2%	5.7
1.5:1 (CH_4: N_2)	0.36	170	135	23.2	30.8%	4.7
1.9:1 (CH_4: N_2)	0.38	160	140	26.2	31.7%	5.4

Figure 22 shows the NO_x emissions as a function of equivalence ratio for natural gas and for the methane-carbon dioxide simulated landfill gas. Figure 23 shows the NO_x emissions as a function of equivalence ratio for natural gas and for the methane-nitrogen simulated landfill gas. As anticipated, the NO_x emission levels decrease at lower equivalence ratios. The NO_x emission levels for simulated landfill gas were similar to that of natural gas.

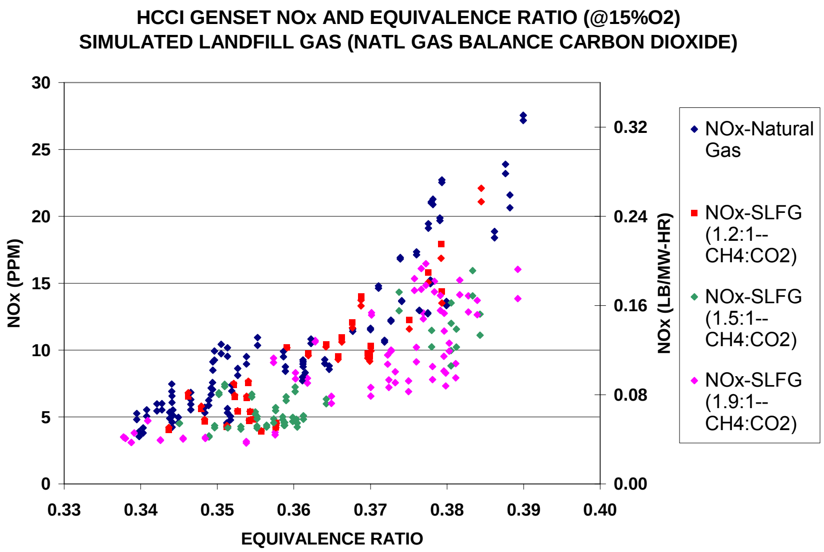


Figure 22 - HCCI Performance – Carbon Dioxide, NO_x Emission Levels and Equivalence Ratio

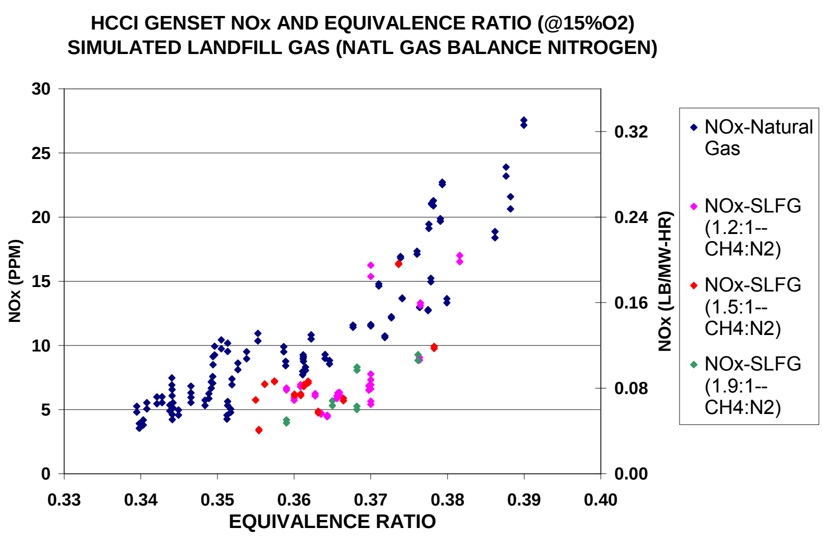


Figure 23 - HCCI Performance – Nitrogen, NO_x Emission Levels and Equivalence Ratio

3.5 Landfill Installation

3.5.1 LFG Collection System

The following is a description of the collection system: Figure 24 shows the major portion of the landfill that has been capped for closure. The cap consists of one foot of soil, topped with a low permeability (1X10-4 cc per minute) adobe, then a 40 mil plastic cover and finally another foot of earth topped with native grasses. Figure 25 shows the individual well heads inserted into the landfill body and then connected to the gas collection delivery piping to convey the LFG to the flaring station where the HCCI generator was be located.

Figure 24 Land fill cap with gas collection wells

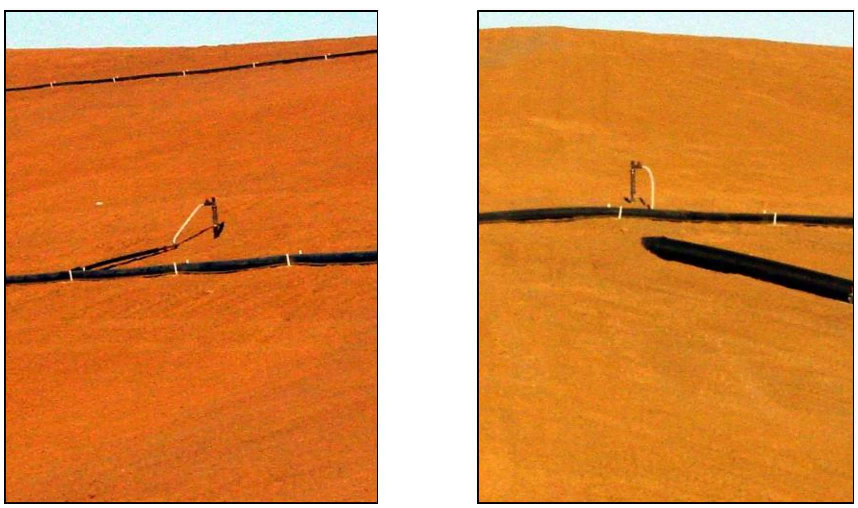


Figure 25 Landfill cap and wells

The following is a description of the major components of the flaring station: Figure 26 shows the overall system with blowers and flare tower. Figure 27 shows the LFG collection system's flare dehumidifier, blowers and control panel. The dehumidifier removes moisture from the landfill gas. Figure 28, Figure 29 and Figure 30 are close-ups of the blower motor which pulls the LFG from the collection system, the temperature and pressure gauges downstream of the blowers just before it enters the flare. Figure 31 and Figure 32 show the control system and rotary screw compressors and vertical air tank. Figure 33 shows the PG&E power hookup and service pole, providing easy access to the power grid once appropriate power synchronization and safety disconnect hardware is installed as part of task 2.7.

Figure 26 Flare station

Figure 27 LFG dehumidifier, blower and control panel

Figure 28 Fuel blower that pulls LFG through the dehumidifiers into the flare

Figure 29 LFG fuel temp downstream of the blower before it enters the flare

Figure 30 LFG fuel pressure downstream of the blower before it enters the flare

Figure 31 LFG flare station control panel

Figure 32 Rotary screw compressors

Figure 33 PG&E meter and service pole at the East end of flare station

3.5.2 LFG Delivery System

The delivery system is comprised of: shutoff valve, piping, activated carbon filter and anti-vibration connection. The following depicts the main component of the engine fuel delivery system. Figure 34 depicts a 3-D rendering of the engine delivery system. The shutoff valve is shown in Figure 35. The main piping is shown in Figure 36. Figure 37 depicts the activated carbon filter unit which holds 200 lb of activated carbon in a 55 gallon drum. Figure 38 shows the P, G & E power drop and engine site. Table 18 is a complete parts list for the engine manifold delivery system

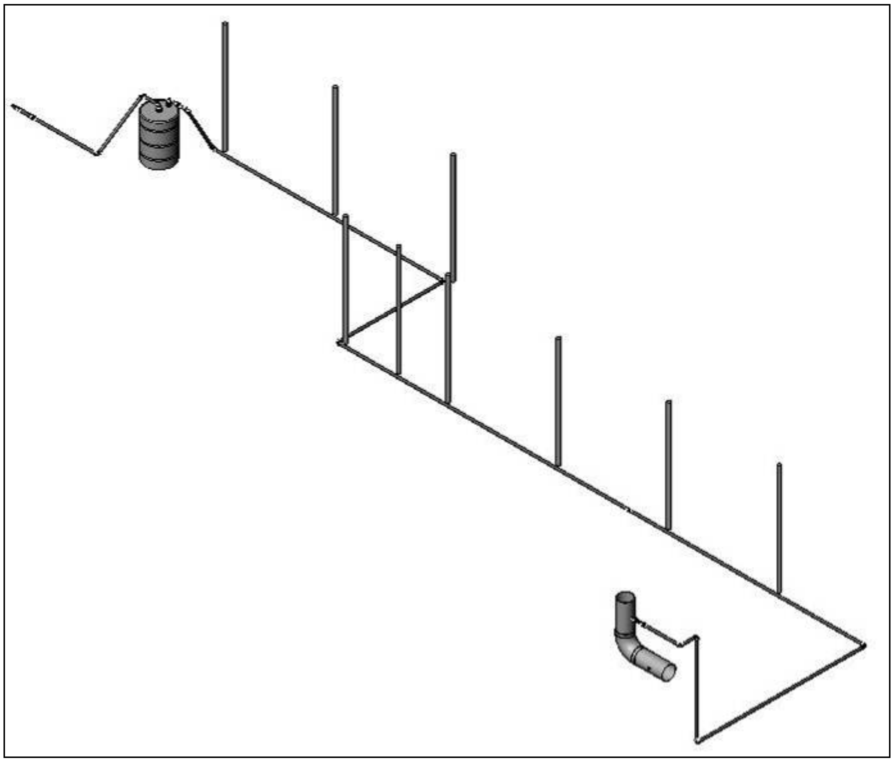


Figure 34 3-D model of delivery manifold

Figure 35 Delivery manifold connection to flare ducting with shutoff valve

Figure 36 Delivery manifold piping

Figure 37 Delivery manifold carbon filter

Figure 38 Power pole and engine site

Table 18 Task 2.6 parts list

Item	QTY	Vendor#	Vendor	Description
FILTER				
Item	QTY	Vendor#	Vendor	Description
Air purification canister	1	G-1S	CARBTROL	Polyethylene lined steel drum w/200 lbs activated charcoal:rated @ 100 cfm
FITTINGS				
Item	QTY	Vendor#	Vendor	Description
Elbow	10	4638K137	MCM	Galvanized Malleable iron pipe fitting-150psi 1.5"Pipe, 90 degree elbow
Valve	1	46495K63	MCM	316 stainless steel full port ball valve lockable lever handle, 1" NPT female
Union	3	4638K737	MCM	Galvanized Malleable iron pipe fitting-150psi 1.5"Pipe, union
Coupling	2	4638K118	MCM	Galvanized Malleable iron pipe fitting-150psi 1.5"Pipe, Coupling
Nipple 1"	1	4549K614	MCM	Galvanized welded steel nipple, schedule 40-1" pipe, 3" length, 1" threaded ends
Reducing Nipple 1	1	7818K223	MCM	Smooth flow reducing pipe nipple, schedule 80- 1.5" X 1" length 4.5"
Nipple 2"	2	4549K671	MCM	Galvanized welded steel nipple, schedule 40-1" pipe, 2" length, fully threaded
Reducing elbow	2	4638K295	MCM	Galvanized Malleable iron pipe fitting-150psi 2" X 1.5"Pipe, 90 reducing degree elbow
Nipple 1.5"	2	4549K661	MCM	Galvanized welded steel nipple, schedule 40-1.5" pipe, 6" length, 1" threaded ends
Braided hose	1	5680K221	MCM	Type 321 SS hose w/ type 304SS braid w/ male X male fittings 12" L, 1.5" D 531 psi
Reducing nipple 2	1	7818K224	MCM	Smooth flow reducing pipe nipple, schedule 80- 1.5" X 1.25" length 4.5"
PIPING				
Item	QTY	Length (ft)	Vendor	Description
1.5" Galvanized	1	21	BI-RITE	252" threaded both ends
1.5" Galvanized	1	17	BI-RITE	204" threaded both ends
1.5" Galvanized	1	16.5	BI-RITE	198" threaded both ends
1.5" Galvanized	1	4.5	BI-RITE	54" threaded both ends
1.5" Galvanized	2	3.67	BI-RITE	44" threaded both ends
1.5" Galvanized	1	1.33	BI-RITE	16" threaded both ends
1.5" Galvanized	1	12	BI-RITE	144" threaded both ends
1.5" Galvanized	1	6.5	BI-RITE	78" threaded both ends
1.5" Galvanized	1	2.5	BI-RITE	30" threaded both ends
1.5" Galvanized	1	7.5	BI-RITE	90" threaded both ends
1.5" Galvanized	1	1	BI-RITE	12" threaded both ends

3.5.3 Installation and Instrumentation

The installation of the HCCI generator at NRL was the next step towards the operation of the engine on actual landfill gas. The shelter provides protection the weather elements as well as security from unwanted guests. Two types of instrumentation at NRL were installed; the electrical grid connection and the fuel flow control system.

MEI completed the following during this task:

- Site Development
    - Gravel Pad and Protective Structure
    - Electrical Disconnect and Transformer
- HCCI Generator Relocation
    - Installed HCCI Generator and Equipment
    - Installed Instrumentation
- Pacific Gas & Electric Interconnection
    - "Rule 21" Interconnection Process

3.5.3.1 Site Development

In preparing for the HCCI generator to be installed at NRL, MEI provided a secure place for the genset to rest for landfill gas testing. The appropriate power was routed to the engine's resting site as well.

Gravel Pad and Protective Structure

A 21 foot by 20 foot gravel test pad was located where the HCCI generator would be installed. Figure 39 shows the gravel test pad. A 21 foot by 18 foot by 10 foot tall temporary protective structure was installed by CALIFORNIA CARPORTS of Madera, CA. This structure is shown in Figure 40.

Figure 39 - Gravel Test Pad

Figure 40 - Protective Structure

Electrical Connections

In preparation for the electrical connections to the HCCI generator to be made, the main 480 VAC disconnect switch and power transformer were installed. The disconnect switch is a heavy duty 480 VAC 100 Amp, CUTLER HAMMER (p/n DH363FRK) fused disconnect switch. The transformer is a 30 kVA, 480VAC/208Y SIEMENS (p/n 3F3Y030) power transformer. The disconnect switch and transformer are shown in Figure 41.

Figure 41 - 480 VAC Disconnect Switch and Power Transformer

3.5.3.2 HCCI Generator Relocation

Relocating the HCCI generator required the coordination of NRL resources and a local flatbed towing service. Arrangements were made to take the other necessary equipment to NRL. The electrical instrumentation was installed as well as the fuel flow control system.

HCCI Generator and Equipment

Utilizing a local towing company the HCCI genset was loaded onto a flat bed hauler and driven to NRL. Images of the relocation of the engine are shown in Figure 42 and Figure 43. Once on-site, a forklift operator from NRL was able to place the genset in the proper location (Figure 44) for the fuel lines to be connected. The soft start and associated wiring were then installed. The load bank was relocated as well. Figure 45 shows the soft start and load bank in their respective place near the installed engine.

Figure 42 - HCCI Loaded Onto Flatbed

Figure 43 - HCCI Unload At Neal Road Landfill

Figure 44 - HCCI Moved into Position by Forklift

Figure 45 - Soft Start and Load Bank Installed

Instrumentation

The Pacific Gas & Electric (PG&E) “Rule 21” interconnection requirement calls for redundant protective relays to be installed on the 480 VAC lines to monitor power output. MEI acquired two BASLER (p/n BE1-IPS100) protective relays. The protective relays were installed as shown in Figure 46. Section 3.6.2 of this report details the PG&E interconnection.

Figure 46 - Redundant Protective Relays

As part of the generator's fuel control system, the proportional fuel flow control valve was installed (see Figure 47). Utilizing a linear stepper motor coupled to a 3-way valve, proportional control over the landfill gas fuel flow is achieved. Using feed back from a methane sensor shown in Figure 48 and a control algorithm, the 3-way valve positions itself between leg A and leg B of the fuel line. Figure 49 is a CAD model and picture of the proportional control valve system. This sub-system is capable of delivering the appropriate amount of LFG to the engine minimizing pressure drop through the fuel line. This mechanism will be used during the on-site tuning of the engine" (task 2.8) Table 19 shows the anticipated flows and induced pressure drops for the maximum and minimum flow conditions expected during landfill gas testing.

Figure 47 - Proportional Control Fuel Valve Installed

Figure 48 – Methane Sensor Installed in Intake Line

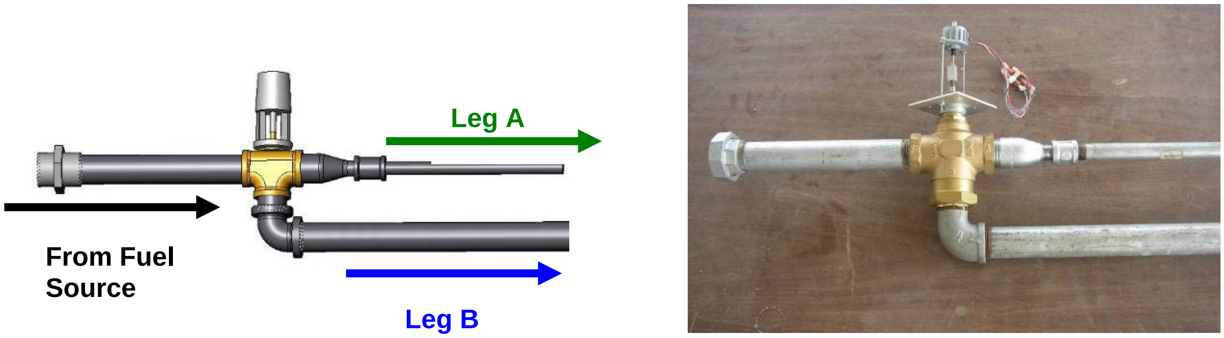


Figure 49 - Proportional Control Valve (Leg A and Leg B)

Table 19 - Proportional Valve Maximum and Minimum Flow Conditions

Equivalence Ratio	LFG-Methane %	Leg A Flow (kgph)	Leg B Flow (kgph)
0.38	30%	0.0	~18.0
0.32	60%	~6.0	0.0

3.5.3.3 PG&E Interconnection

Working with PG&E, MEI continued through the "Rule 21" interconnection process. The interconnection requirements for Distributed Generation (DG) are determined by the California Public Utilities Commission (CPUC). Electric Rule 21 outlines the interconnection, operational and metering requirements for generating facilities that are connected to the PG&E distribution system. Additional information can be found in the installation report (Installation of Engine and Instrumentation).

3.6 Landfill Gas Operation - Tuning

The tuning of the engine to operate on LFG served as the next step towards Field Testing. The following sections illustrate the steps that were taken in order for the HCCI genset to operate on LFG. "Tuning" was comprised of adapting the HCCI genset's fuel and thermal control system for operation of the HCCI genset using landfill gas as a fuel source. This included the re-development of the fuel delivery system and the development of a control code for automated individual cylinder temperature control. The tuning of the genset "on-site" also included the completion of the Rule 21 grid interconnection as set forth by Pacific Gas and Electric Company (PG&E) which required 3rd party verification of the protective relays settings.

MEI completed the following during this task:

- Modified Fuel Delivery System
  - Porting into LFG Flare Header
  - 2.5" pipe ducting
- Pacific Gas & Electric Interconnection
  - "Rule 21" Interconnection Process
  - Instrumentation-3rd Party Verification
- Thermal Conditioning Modification
  - Trim Control Hardware
  - Control Code Development
- Operation on LFG
  - Tuned Operation

3.6.1 Modified Fuel Delivery System

The original fuel delivery system was installed as part of task 2.6. Butte County had allowed MEI to install the delivery ducting at the existing 1 inch pipe port shown in Figure 50. Upon preliminary testing with LFG, it was determined that the fuel delivery ducting and port needed to be re-sized. The port size was increased from a diameter of 1.25 inches to a port size diameter of 4.0 inches significantly decreasing the pressure drop the fuel delivery line. Figure 51 shows the new port and Figure 52 shows the relative increase in pipe diameter

Figure 50 - Original Port

Figure 51 - Modified Port

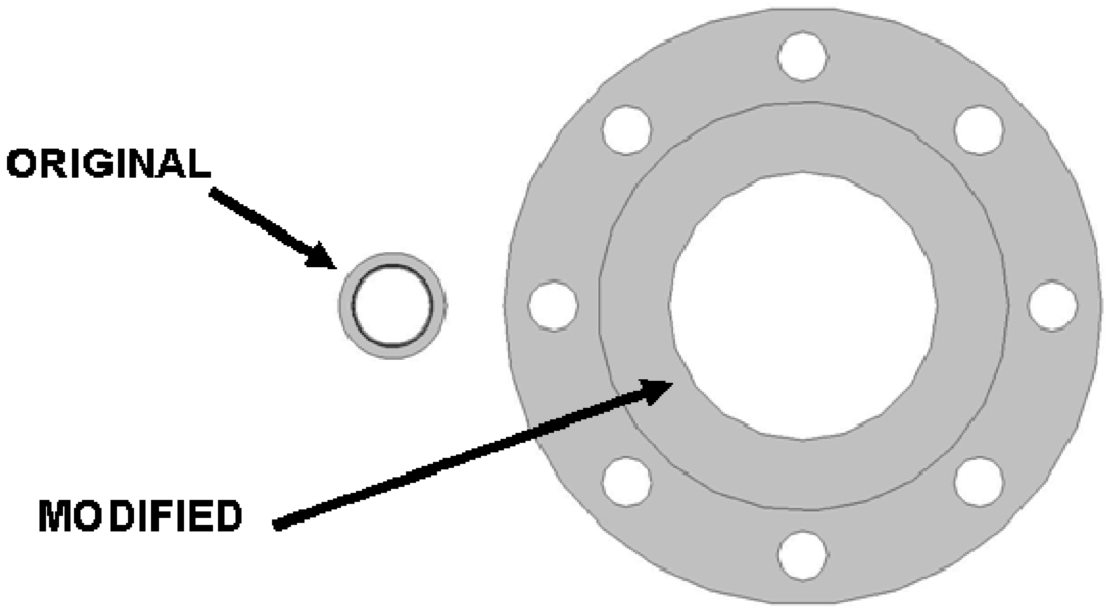


Figure 52 - Increased Port Size Illustrated

3.6.1.1 Porting into LFG Flare Header

Modifying the ducting required welding a 4.0 inch pipe stub onto the main flare pipe. To do this, the flaring station had to be shut down. MEI amassed the necessary ducting components awaiting word the flare station would be shutdown. Finally the flare was shutdown and the main flare pipe was removed to have the 4" pipe stub welded as shown in Figure 53. The pipe stub was welded, a butterfly valve attached and the new, 2.5" ducting was installed as shown in Figure 54.

Figure 53 - Flare main removal

Figure 54 - 4 inch flanged pipe stub to be welded onto flare main

3.6.1.2 2.5 inch Piping

The new, larger diameter delivery ducting shown in model Figure 55 and installed in Figure 56 including a second activate charcoal filter in parallel, shown in Figure 57. The second filter allows for sufficient filtering while allowing higher LFG flow rates with minimal restriction to the engine.

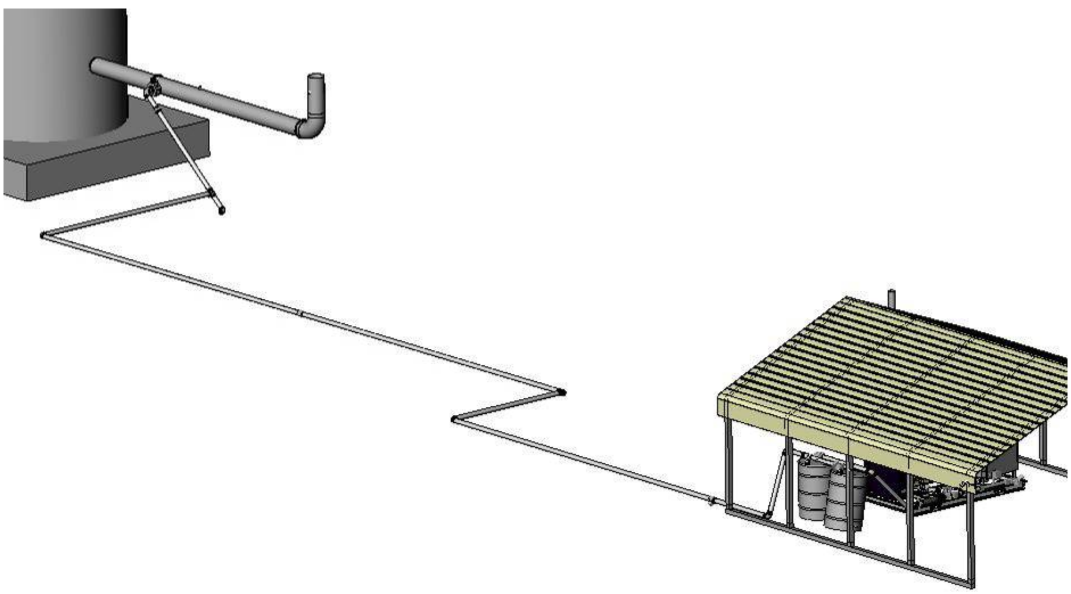


Figure 55 - Model of improved LFG delivery ducting

Figure 56 – LFG delivery ducting installed

Figure 57 - Dual Activated Charcoal Filters

3.6.2 PG&E Interconnection Completed

MEI successfully connected the HCCI genset to the Pacific Gas & Electric (PG&E) electrical grid. The power that is generated offsets the power required at the Landfill's flaring station while the excess is burned off in a load bank.

3.6.2.1 "Rule 21" Interconnection Process

Working with PG&E, MEI completed the "Rule 21" interconnection process. The interconnection requirements for Distributed Generation (DG) are determined by the California Public Utilities Commission (CPUC). Electric Rule 21 outlines the interconnection, operational and metering requirements for generating facilities that are connected to the PG&E distribution system. This process took 12 months to complete. The schematics for the PG&E interconnection can be found in Appendix I of the Tuning report (Tune Engine on site of Operation on LFG). MEI was directed towards a "parallel non-export" type of interconnection by PG&E.

3.6.2.2 Instrumentation -3rd Party Verification

The Pacific Gas & Electric (PG&E) "Rule 21" interconnection requirement calls for redundant protective relays to be installed on the 480 VAC lines to monitor power output. Two Basler BE1-

IPS100 Intertie Protection System relays protect, monitor and control the interconnection between MEI's HCCI genset and the PG&E grid. The outputs on the Basler relays are normally open and connected in series with an auxiliary mechanical relay (TYCO P/N KRP-5AG-120). The relay contacts are programmed to be held closed and will open on failure if any one of three conditions occurs. These conditions include:

- A trip condition is asserted
- Internal diagnostics indicate a relay failure
- Power is lost to the relay

The main contactor actuating circuit for the motor contactor is connected through a normally open contact on the auxiliary mechanical relay. When the at least one of the failure conditions occur, the auxiliary mechanical relay is de-energized opening the circuit to the main contactor. The contactor will then open breaking the connection between the generator and the grid. There are no other switches or device contacts in the relay trip circuit.

The protective relays were installed as shown in Figure 46. The protective relays essentially serve as a switch which "opens" disconnecting the generator from the grid when the generated power is out of PG&E mandated specifications. The protective relay settings for which a "trip" condition exerts itself are listed in Table 20

Table 20 – Basler Protective Relay Settings

Device #	Function	Trips Breaker	Trip Setting	Duration
51P	Time Overcurrent	OUT1 (open)	5.0 A, Curve I2, time dial = 2.0	Inverse time
59P	Overvoltage	OUT1 (open)	110% or (132 V on 120 V base)	50 ms
27P	Undervoltage	OUT1 (open)	88% or (105.6 V on 120 V base)	50 ms
181	Overfrequency	OUT1 (open)	60.5 Hz	160 ms
81	Underfrequency	OUT1 (open)	59.3 Hz	160 ms
32	Underpower	OUT1 (open)	21.6 W (1 of 3) forward under	50 ms

Part of the "Rule 21" requirements is to have a 3rd Party verify the protective relays settings. HART High-Voltage of Yuba City conducted this verification for MEI. Figure 59 shows the test equipment used HART to simulate the trip conditions listed above. A representative from PG&E (Mr. Ron Divine) witnessed the relay testing as part of the Pre-Parallel Inspection and gave MEI the approval to operate the generator while connected to the grid.

Figure 58 - Basler Redundant Protective Relays

Figure 59 - 3rd Party Relay Test Equipment

3.6.3 Thermal Conditioning Modifications

Baseline testing at MEI's test facility (outlined in task 2.3 and 2.4) allowed for initial development of the Individual Cylinder Temperature Control (ICTC) intake system. Temperature control of each cylinder allowed for optimization of the system outputs. For field testing, automated control of the temperatures for the ICTC was needed. This section describes the hardware and control code which allowed for a prescribed set temperature for each cylinder to be maintained.

3.6.3.1 Trim Control Hardware

Hardware included the installation of six (one per cylinder) mechanical relays in the trim heating control circuitry. Shown in Figure 42, the relays are controlled by a relay rack which is interfaced to the host PC.

Figure 60 - Mechanical Relays for ICTC

3.6.3.2 Control Code Development

MEI developed the control software using DELPHI, an object oriented Pascal based software development package. This platform allowed for automated trim heating of the ICTC intake system. Figure 61 shows the temperature response for cylinder #2. The blue line is a preliminary temperature response to the temperature control for cylinder #2; note the large temperature variation. The pink line shows the response for temperature control to after further development of the control code; note that the temperature is being held to within 4 degrees of the 255 ^{o}C set point.

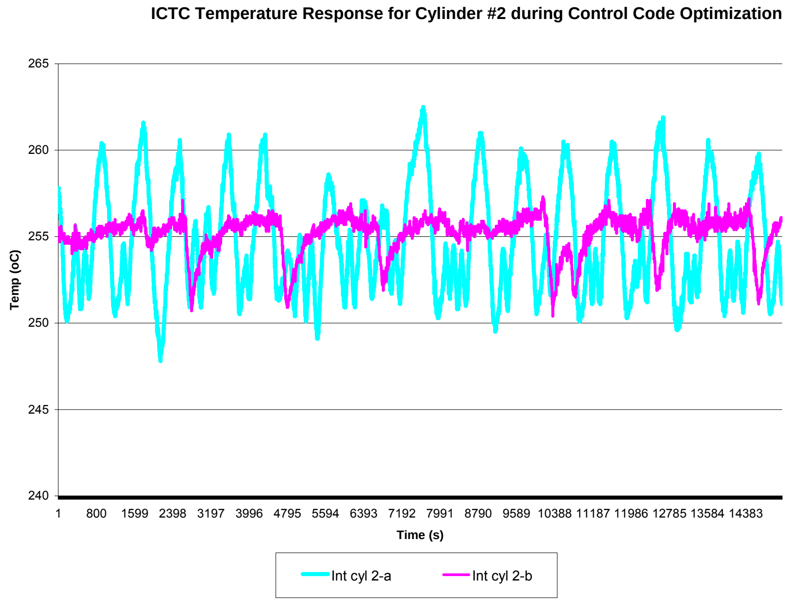
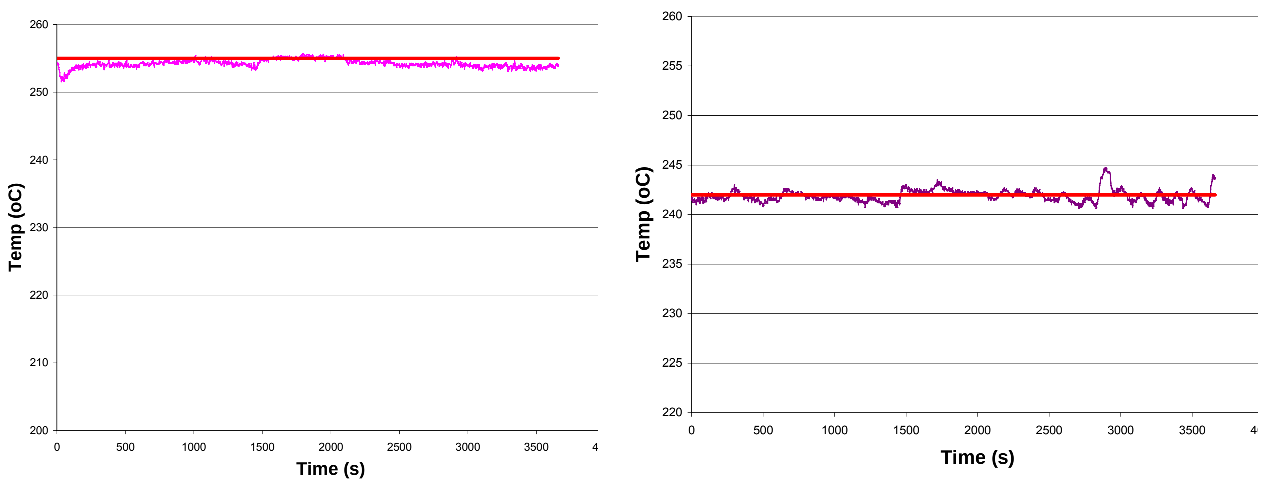


Figure 61 - ICTC Preliminary Temperature Response

Through the adjusting of response time and cycle time, the trim heaters are now capable of holding a desired temperature set point. .Figure 62 shows the temperature response for cylinders #1 and #4 along with their corresponding set points.



.Figure 62 - Temperature Response for CYL #1 (left) -#4 (right)

3.6.3.3 Engine Block Operating Temperature

Bench testing with natural gas and simulated LFG was conducted at inlet temperatures of approximately 185°C and block temperatures of 135°C to 145°C. Bench testing indicated that a correlation between lower block temperatures and lower NO_X emissions exists. During LFG operation, the engine block was operated at lower temperatures producing low NO_X emissions. Increased block and inlet temperatures produced higher system efficiency, however resulted higher NO_X emissions. To achieve a balance between engine efficiency and NO_X emission levels, the engine was operated at the regions shown in green on the plots shown in Figure 63 and Figure 64. Figure 63 shows the resulting efficiency as a function of inlet temperature and block temperature. Figure 64 shows the resulting NO_X emissions as a function of inlet temperature and block temperature.

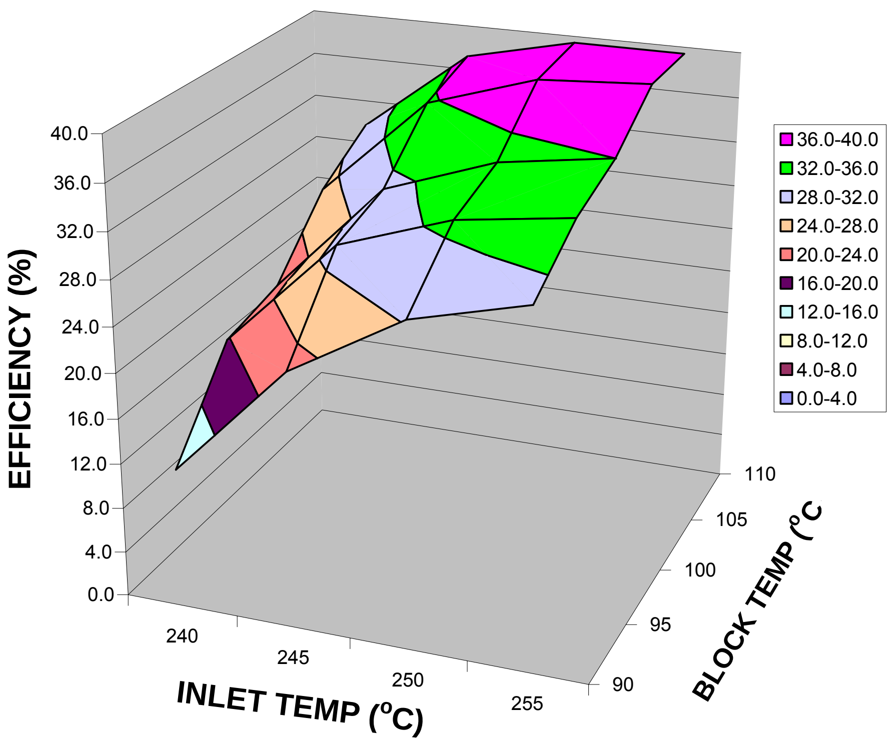


Figure 63 – Efficiency as function of Inlet Temp and Block Temp

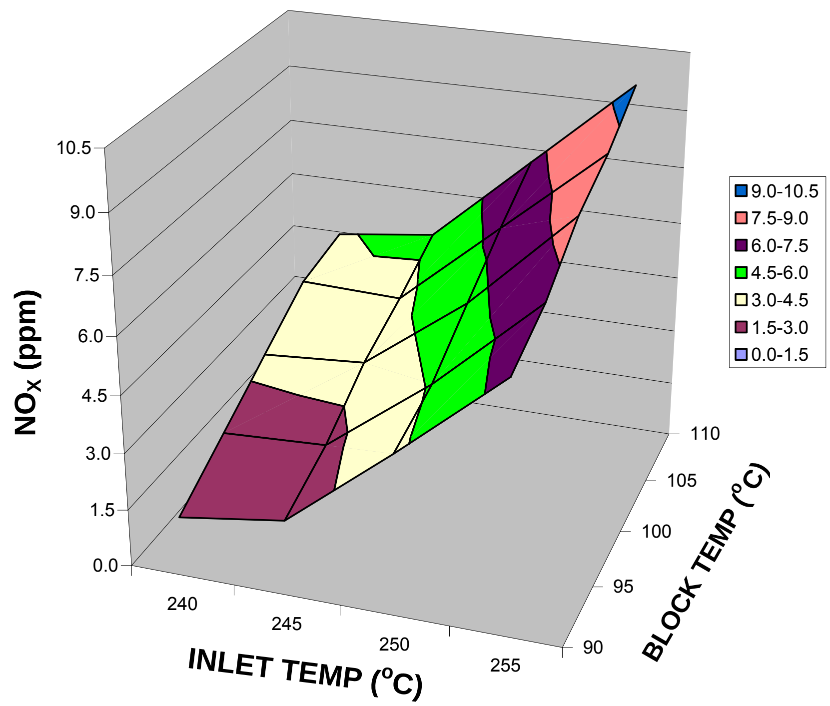


Figure 64 - Emissions as function of Inlet Temp and Block Temp

This additional mapping allowed for an optimal inlet and engine block temperature range to be determined. The engine block was operated at lower temperatures than bench testing while the intake temperature was increased. Further LFG field testing was then conducted at inlet temperatures of approximately 245°C to 250°C and block temperatures of 100°C to 105°C. The modified operating conditions improved system efficiency when compared to the bench testing.

3.6.4 Preliminary Operation on LFG

Testing with LFG for this task was limited due to the PG&E interconnection process. The engine was not to be operated until the Pre-Parallel Inspection was conducted by PG&E. Once this was completed, ongoing testing with LFG commenced.

3.6.4.1 Tuned Operation

With the addition of automated trim heating control, after only a few hours of operation, the HCCI genset became stable. A plot of the efficiency, NO_X output and equivalence ratio is shown in Figure 65. The engine achieved about 36% efficiency with approximately 6.0 ppm NO_X while producing 25kW of electricity. The engine was considered “tuned.”

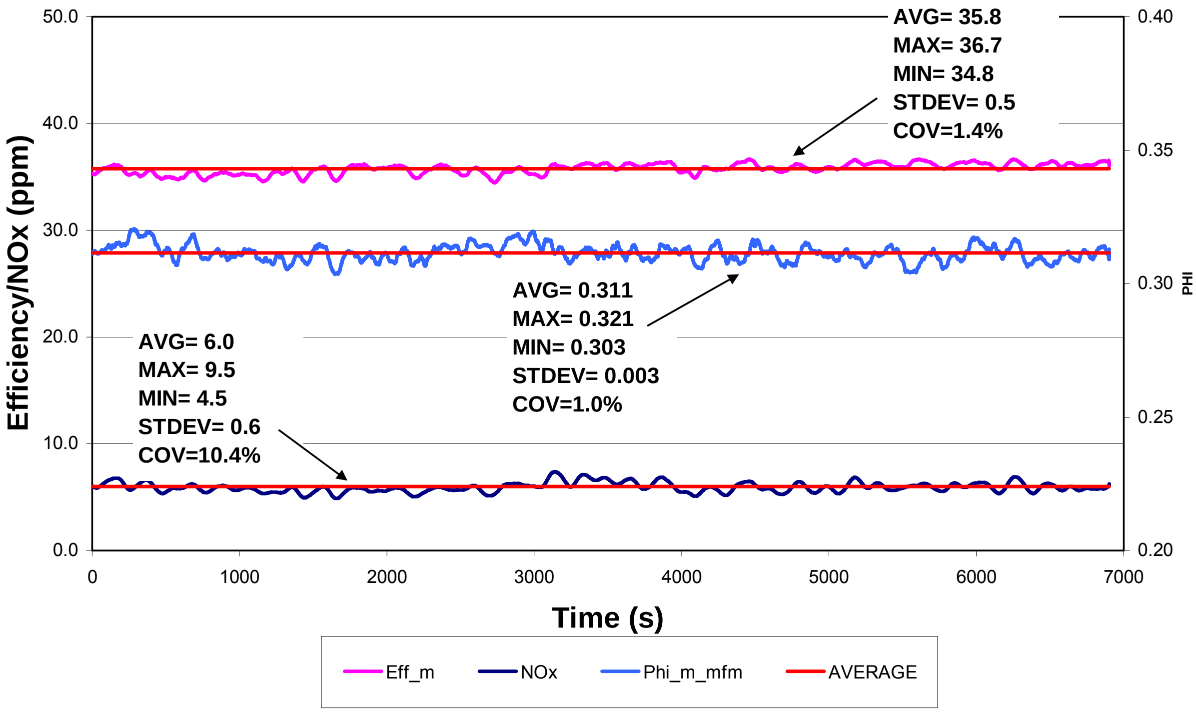


Figure 65 - Stable Engine Performance

3.7 Landfill Gas Operation – Field Testing

3.7.1 Test Plan Overview

Field Test Plan, task 2.9, details can be found in the Field Test Plan document. It conveys the series, rationale and expected outcomes for the testing associated with task 2.10, task 2.11 and task 2.12 of this project. This entailed efficiency, stability, and durability testing as performed by MEI on the HCCI genset as installed at the Neal Road Landfill (NRL). Efficiency testing would comprise adjusting the inlet temperature and fuel input levels until the highest efficiency and power output is reached while meeting project emission goals. Stability testing would include the verification of less than 10% variance from the optimized conditions set forth by efficiency testing. Durability testing would include monitoring of the optimized conditions and engine oil degradation during all daily testing (approximately 30 hours per week) plus three continuous intervals (48 to 100 hours).

The field tests that were conducted and are summarized in as follows:

3.1 Efficiency Testing

- 3.1.1 Determining LFG Bulk Inlet Temperature
- 3.1.2 Determining Optimal Individual Inlet Temperatures

3.2 Stability Testing

- 3.2.1 Stability with LFG Fuel Source

3.3 Durability Testing

- 3.3.1 Daily Durability Testing
- 3.3.2 Continuous Durability Testing

3.7.2 Landfill Gas Operation Results Summary

MEI successfully operated the HCCI genset using LFG as fuel for 510 hours with stable performance. The engine was operated for daily runs (6-10 hours per run) and for extended runs (24 to 95 hour intervals). The engine performance was monitored for efficiency and power output as well as NO_X emission goals. Figure 66 shows the monthly and cumulative runtimes of all LFG test phases.

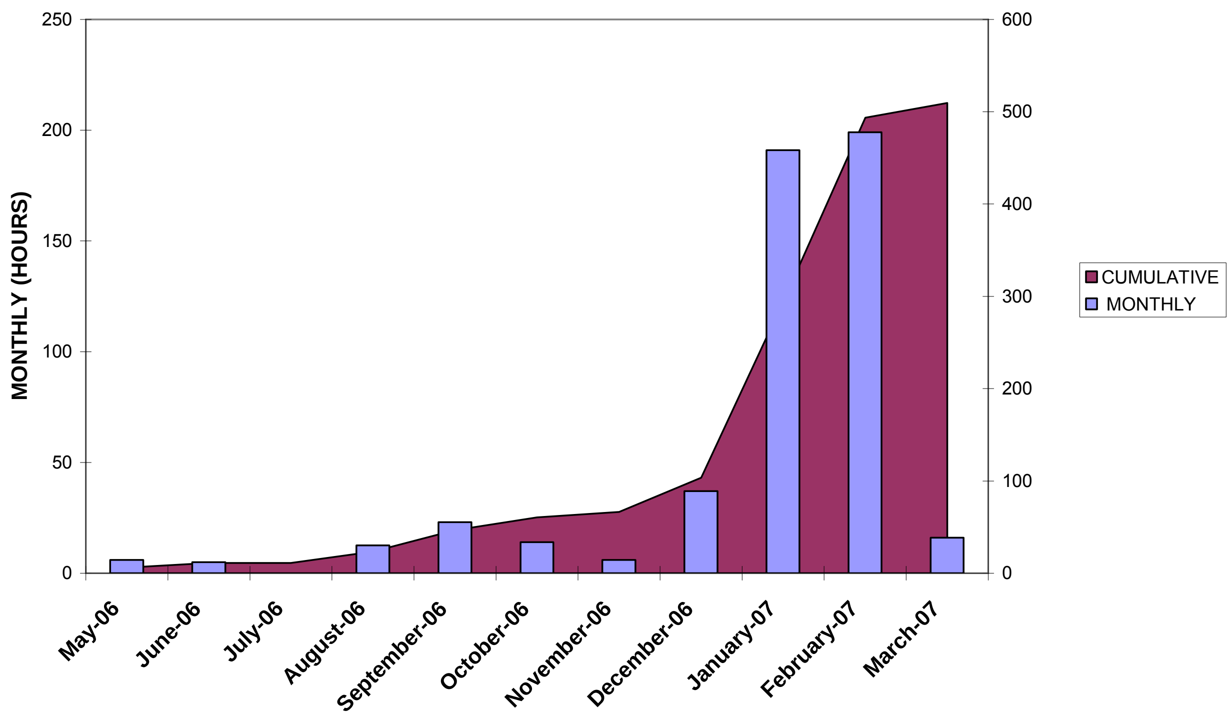


Figure 66 – Monthly Total and Cumulative Runtime for LFG Operation

Table 21 summarizes the results of the field testing. The following sections summarize the results of the efficiency, stability and durability testing.

Table 21 – Field Testing Results

Specific Test	Result
3.1 Efficiency Testing	
3.1.1 Determining LFG Bulk Inlet Temperature	>35% Efficiency & <5.0 ppm NO_X (0.07 lb/MW-hr)
3.1.2 Determining Optimal Individual Inlet Temperatures	
3.2 Stability Testing	
3.2.1 Stability with LFG Fuel Source	Stable <5.0% variation
3.3 Durability Testing	
3.3.1 Daily Durability Testing	>10,000 hours
3.3.2 Continuous Durability Testing	

3.7.2.1 Efficiency Testing Engine Performance

Efficiency testing was defined in the first two sections of the Field Test Plan. Testing consisted of systematic optimization of inlet temperature and air fuel ratio to achieve project emission goals. From this testing, MEI generated an ideal inlet temperature profile. MEI also characterized the emissions, equivalence ratio and efficiency performance.

NO_X versus equivalence ratio and NO_X versus system efficiency plots were generated from the data collected during efficiency testing. Table 22 summarizes the results from the operating conditions explored during efficiency testing. Figure 67 shows a correlation between the NO_X emissions and equivalence ratio achieved.

Table 22 - HCCI Performance with LFG –Operating Conditions

INLET CONDITION			OUTPUT		
EQUIV. RATIO	INTAKE MANIFOLD TEMP(oC)	MAP (BAR)	POWER OUTPUT (kW)	SYSTEM EFFICIENCY	NOx LEVEL (ppm)-(lb/MW-hr)*
0.31	247	1.47	25.4	34.9	3.0 (0.04)
0.33	246	1.49	26.0	36.8	6.0 (0.08)
0.34	245	1.50	27.5	38.9	10.0 (0.12)

*All emission data is corrected for dry 15% oxygen

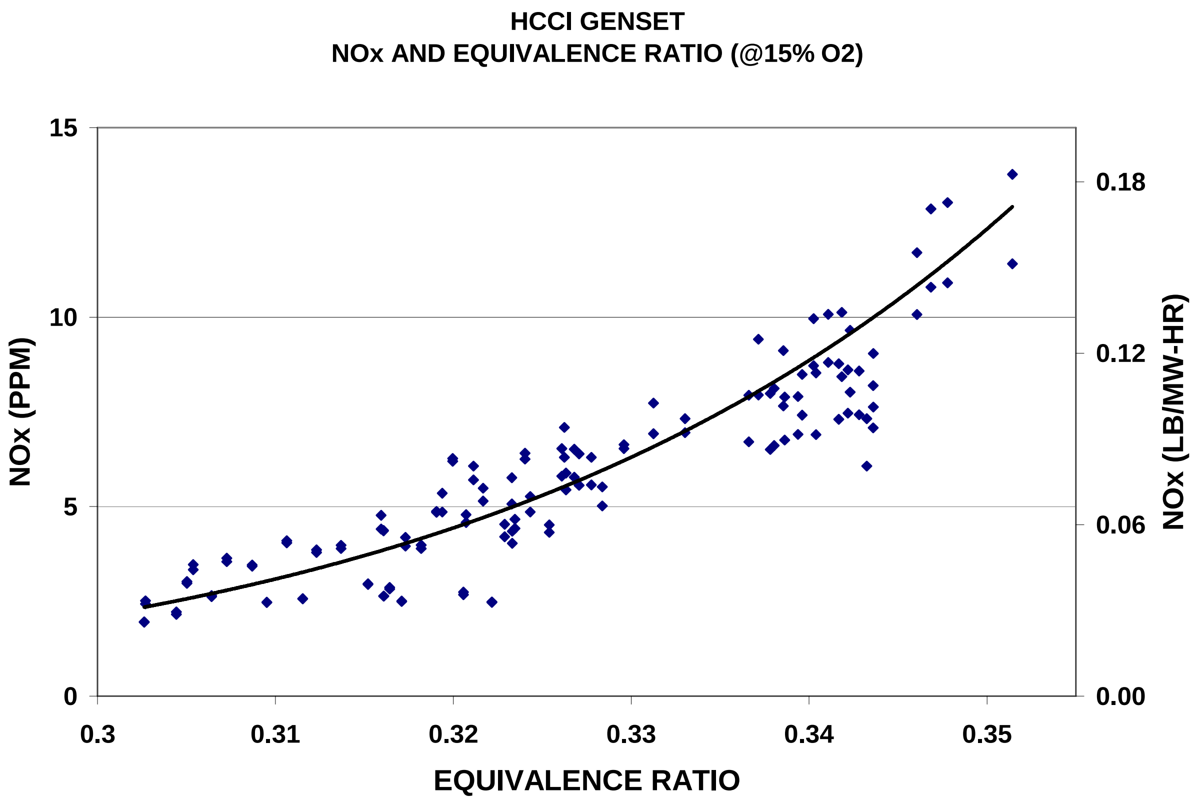


Figure 67 - NO_X Emissions and Equivalence Ratio for LFG

Table 23 summarizes the NO_X emission and system efficiencies achieved during efficiency testing. Figure 68 shows a correlation between the NO_X emissions and system efficiency. The engine is capable of exceeding the project targets for efficiency (>37%) with slightly higher than project targets for NO_X emissions (>9 ppm). Engine operation with slightly reduced system efficiency (<35%) results in NO_X emissions better than the project target (i.e. <5 ppm). Table 24 lists other exhaust species measured.

Table 23 – HCCI Performance with LFG-Efficiency and NO_X

EFFICIENCY (%)	NO_X (ppm)-(lb/MW-hr)*
37-39	8-14 (.10-.17)
33-37	4-8 (.05-.10)
31-33	2-4 (.03-.05)

* All emissions reported @ 15% oxygen

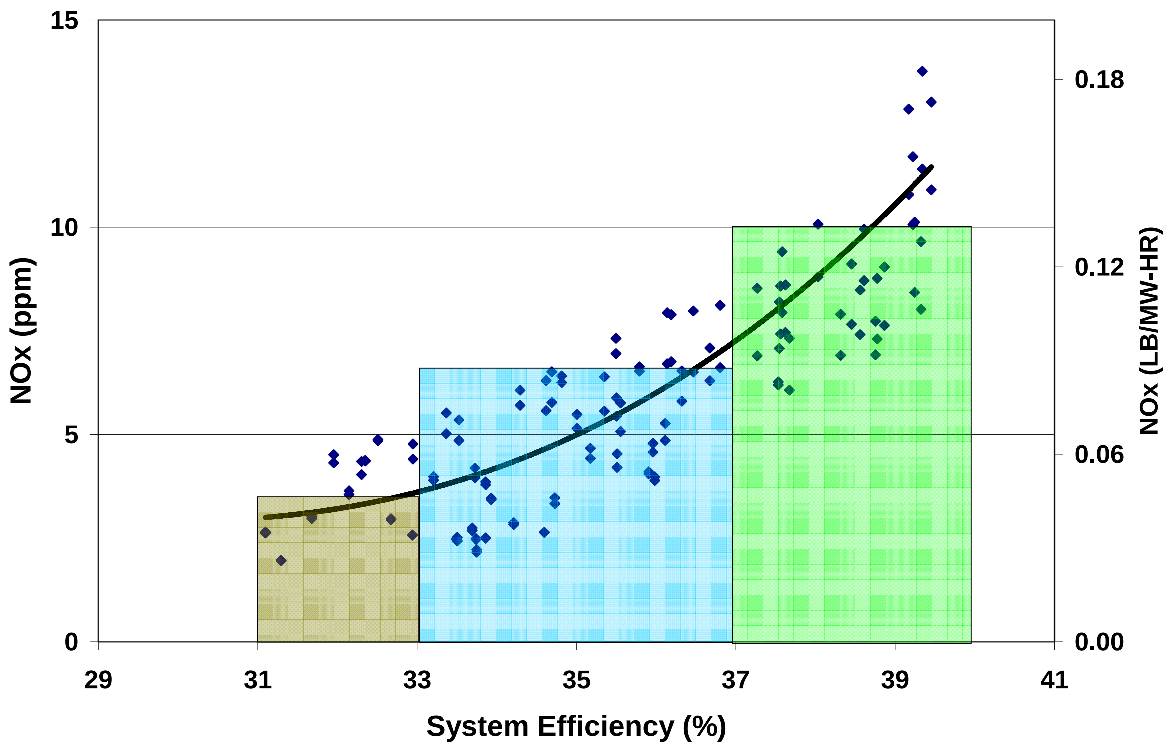


Figure 68 - NO_X Emissions and System Efficiency for LFG

Table 24 - HCCI Performance with LFG –Other Exhaust Gas Species

INLET CONDITION		ENGINE OUTPUT		EXHAUST GAS			
EQUIV. RATIO	INTAKE MANIFOLD TEMP (oC)	POWER OUTPUT (kW)	SYSTEM EFFICIENCY	CO_2 (%)	CO (ppm)-(lb/MW-hr)	UHC (ppm)-(lb/MW-hr)	NO_x (ppm)-(lb/MW-hr)*
0.31	245	25.4	34.9	~9.0	<15.0 (0.12)	8.0 (0.03)	2.9 (0.04)
0.34	245	27.5	38.9	~9.5	<15.0 (0.12)	10.0 (0.04)	9.9 (0.12)

*All emission data is corrected for dry 15% oxygen

Other computed engine performance parameters include: brake power, torque, brake thermal efficiency, specific power (SP), brake mean effective pressure and output per displacement (OPD). Table 25 summarizes these parameters for operation on LFG.

Table 25 - HCCI Performance with LFG-Other Engine Performance Parameters

INLET CONDITION			OUTPUT						
EQUIV RATIO	INT TEMP (oC)	MAP (BAR)	POWER OUTPUT (kW)-[HP]	BRAKE POWER (kW)-[HP]	TORQUE (ft-lb)-[N-m]	BTE (%)	NOx (ppm)	SP (KW/M^2)	OPD (KW/L)
0.31	245	1.44	26.6 (35.7)	28.6 (38.3)	206 (152)	37.4	5.0	550	4.3
0.34	245	1.47	28.7 (38.6)	30.9 (41.5)	223 (164)	40.1	13.3	596	4.7

Determining LFG Bulk Inlet Temperature

After performing the steps outlined in the field test plan, MEI was able to establish the range of inlet temperatures in which LFG auto ignited. Table 26 lists the inlet bulk temperature, corresponding system efficiency and NOx emission level.

Table 26 – Bulk Inlet Temperature Testing Results

Bulk Temp	Stable	Efficiency	NO_X (ppm)*
225	NO	<10	N/A
230	NO	<10	N/A
235	NO	~22	N/A
240	YES	~27	~3
245	YES	~33	~4
250	YES	~35	~6
255	YES	~35	~8
260	YES	~39	~10

* All emissions reported @ 15% oxygen

As expected, system efficiency improved as the bulk inlet temperature increased. For continuous field testing, the bulk inlet temperature was set between 245°C and 255°C. Figure 69 shows the effect lowering the bulk inlet manifold set point temperature from 250°C to 240°C. Notice the decreased efficiency as the inlet temperature is lowered.

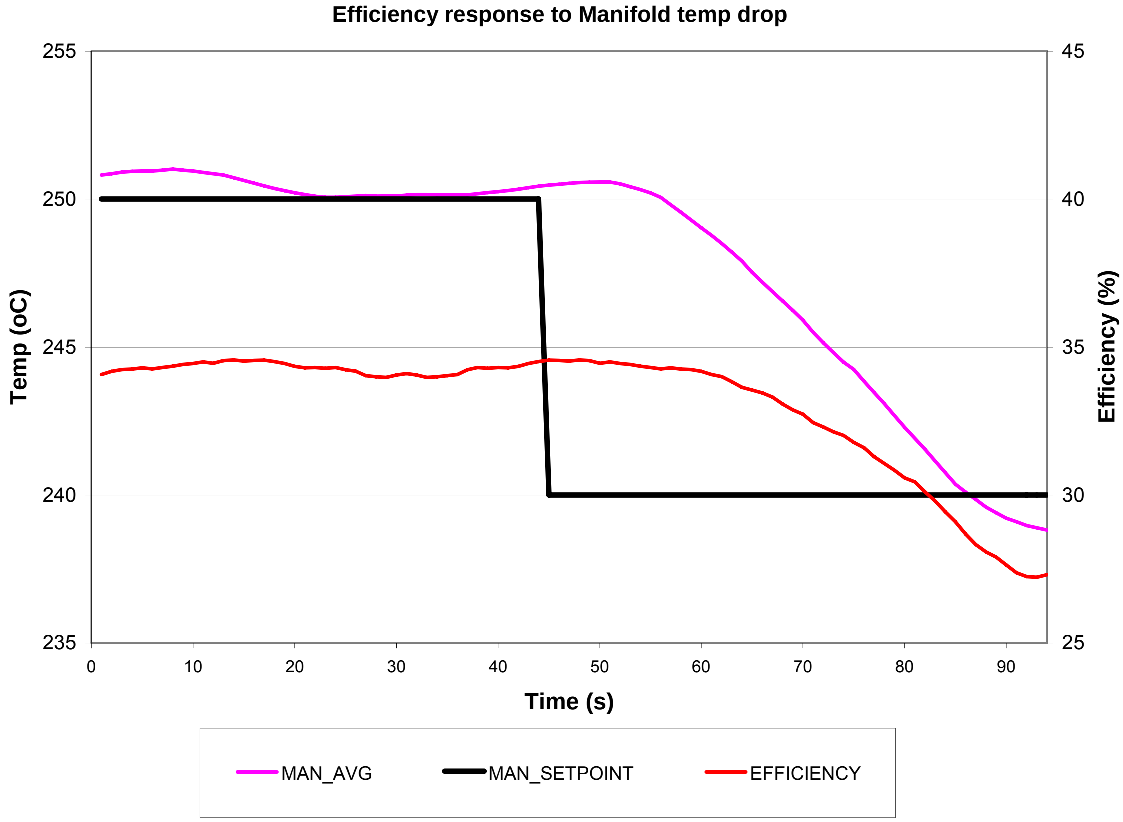


Figure 69 - System Efficiency Response to Lowering of Bulk Inlet Temperature

Determining Optimal Individual Inlet Temperatures

By monitoring the exhaust temperature of each cylinder in conjunction with the system efficiency, an ideal inlet temperature profile was obtained. By operating the engine at a given equivalence ratio and adjusting the individual cylinders, matrices were established for each cylinder. The bulk inlet temperature was set to 245°C during this set of test. All temperature profile testing was conducted at an equivalence ratio of 0.34. Testing resulted in the optimal firing based on the inlet temperature for each cylinder, as listed in Table 27. Figure 70 shows a plot of the optimal inlet temperature profile. The engine was not operated at inlet temperatures exceeding 260°C or exhaust temperatures exceeding 470°C.

Table 27 – Individual Cylinder Inlet Temperature Results

Cylinder #	Inlet Temp. (^{o}C)
T_{LFG-1}	255.0
T_{LFG-2}	245.0
T_{LFG-3}	240.0
T_{LFG-4}	240.0
T_{LFG-5}	240.0
T_{LFG-6}	250.0

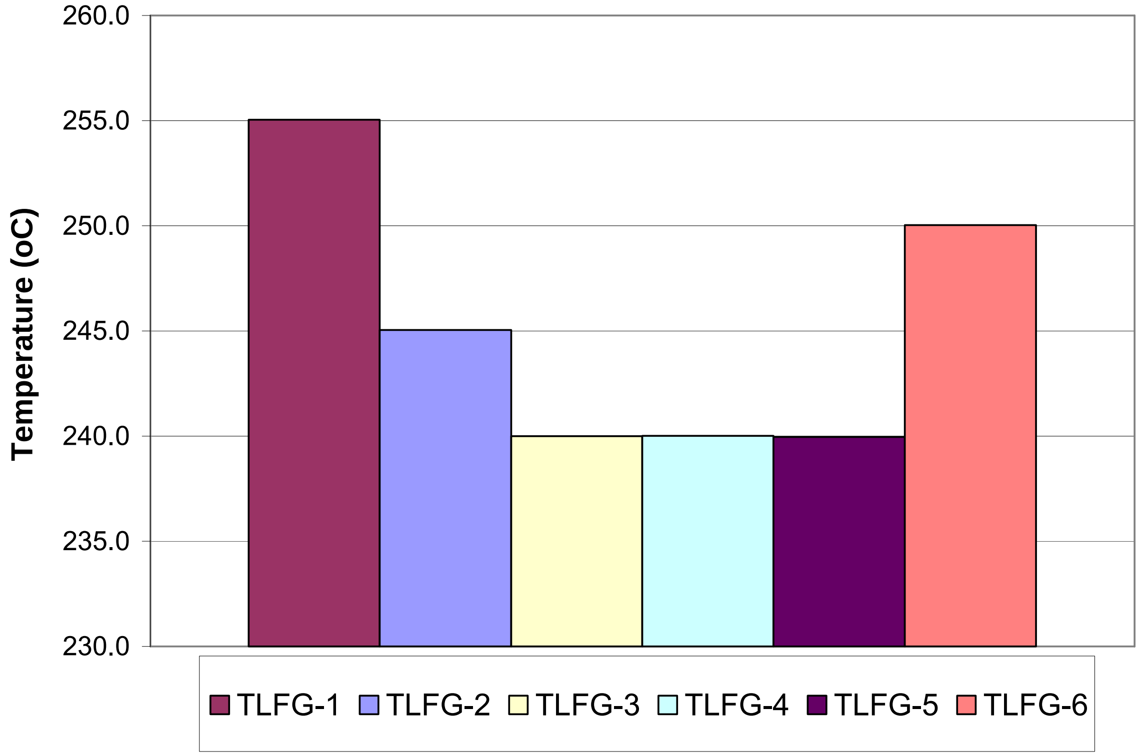


Figure 70 – Optimal Cylinder Inlet Temperature Profile Results

3.7.3 Stability Testing Results

With the engine installed at the Neal Road Landfill, MEI performed five extended runs and over sixty daily runs. The extended runs were broken down into files of up to 4 hours, generating a total of 110 files of data. As described in the Field Test Plan, the coefficient of variation for the system efficiency was used as a measure/verification of engine stability. The maximum coefficient of variation for the system efficiency for the individual files was 4.5%.

The five extended runs were utilized for the detailed discussion presented in the sections that follow. Table 28 summarizes the results for each extended run. For easy reference throughout this report, the extended runs are labeled A-E, with the durations indicated in Table 28. System efficiency, equivalence ratio and NO_X emissions are presented. For each of these engine performance parameters, the average value, maximum, minimum, standard deviation and coefficient of variation were calculated.

Table 28 - Stability Results for Continuous Runs

Run	Duration (hrs)	Parameter	Average	STDEV	MAX	MIN	COV
A	95	NOx (ppm)	8.5	1.5	13.5	3.6	8.9%
		Equiv. Ratio	0.34	0.010	0.371	0.300	3.1%
		Efficiency	38.0	1.2	41.3	34.2	3.2%
B	40	NOx (ppm)	2.6	0.5	4.8	1.4	8.8%
		Equiv. Ratio	0.30	0.007	0.324	0.293	2.3%
		Efficiency	33.8	0.8	36.5	31.3	2.3%
C	28	NOx (ppm)	3.9	0.7	6.8	2.0	9.5%
		Equiv. Ratio	0.32	0.009	0.340	0.298	2.8%
		Efficiency	34.7	1.2	37.5	31.2	3.6%
D	25	NOx (ppm)	4.1	0.8	7.0	2.0	9.8%
		Equiv. Ratio	0.32	0.009	0.338	0.298	2.7%
		Efficiency	35.1	1.1	37.7	32.2	3.1%
E	70	NOx (ppm)	4.4	0.7	6.7	2.5	7.9%
		Equiv. Ratio	0.32	0.006	0.340	0.291	1.8%
		Efficiency	35.1	0.6	37.1	33.0	1.7%

As indicated in Table 28, not all runs were operated at the same conditions. The inlet conditions for run A were set to result the higher end of engine efficiency (equivalence ratio of 0.34, resulting nominal efficiency of 38%, ~8.5 ppm NO_X) and run B conditions were set to result lower end of NO_X emissions (equivalence ratio of 0.30, resulting nominal efficiency of 34% and 2.6 ppm NO_X). Runs C, D and E were set to operate at the point where both efficiency and emissions meet program goals (equivalence ratio ~0.32, resulting nominal efficiency of 35% and 4-5 ppm NO_X).

3.7.3.1 Stability Plots of Efficiency

Figure 71through Figure 75 are the plots of the system efficiency during runs A-E, with the coefficient of variance (the measure for system stability) and additional statistical values (average, standard deviation, maximum and minimum) for each run. The maximum coefficient of variance for the individual extended runs was 3.6%, for run C, as shown in Figure 73. In addition to the individual run variation analysis, it is also possible to compare the three runs targeted for nominal operation at 35% efficiency. The average for run C was 34.7% and for runs D and E, the average was 35.1%, or approximately 1% difference.

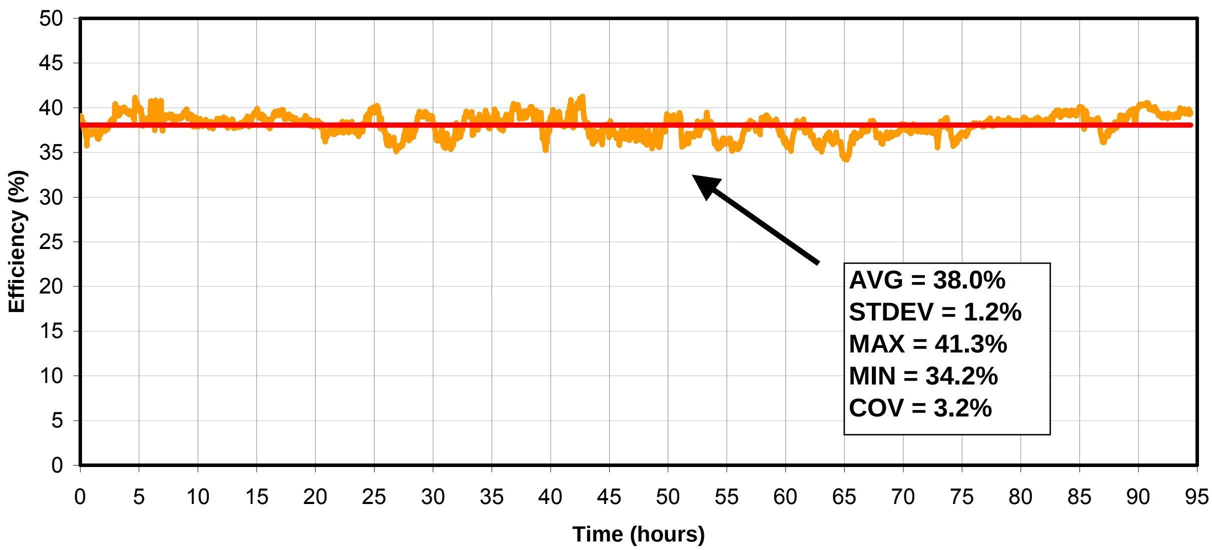


Figure 71 – Run A - Stable LFG Operation- 95 Hours Continuous

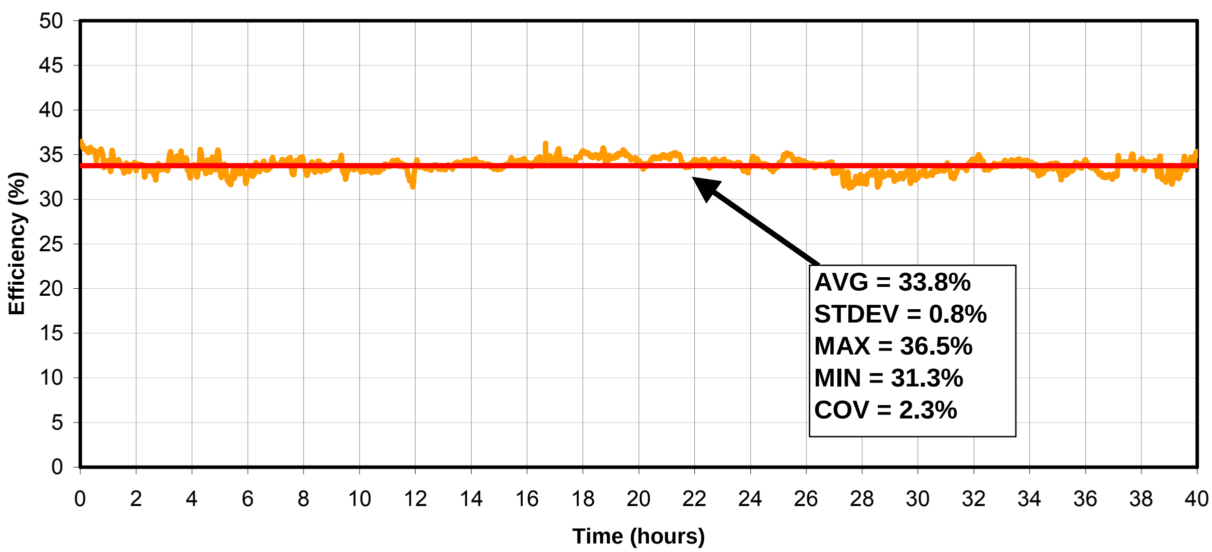


Figure 72 – Run B - Stable LFG Operation- 40 Hours Continuous

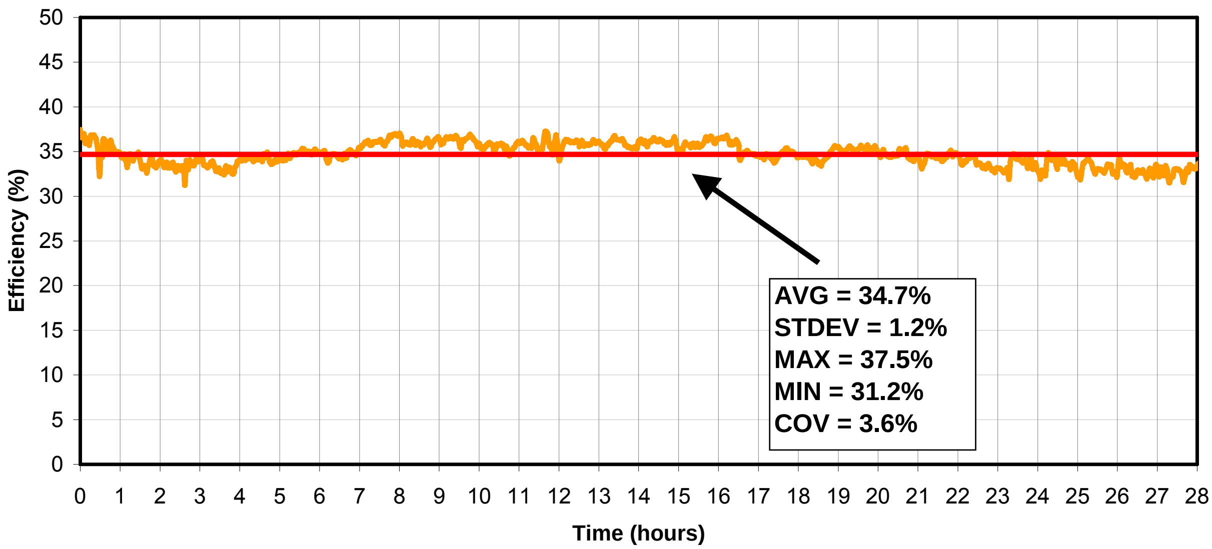


Figure 73 – Run C - Stable LFG Operation- 28 Hours Continuous

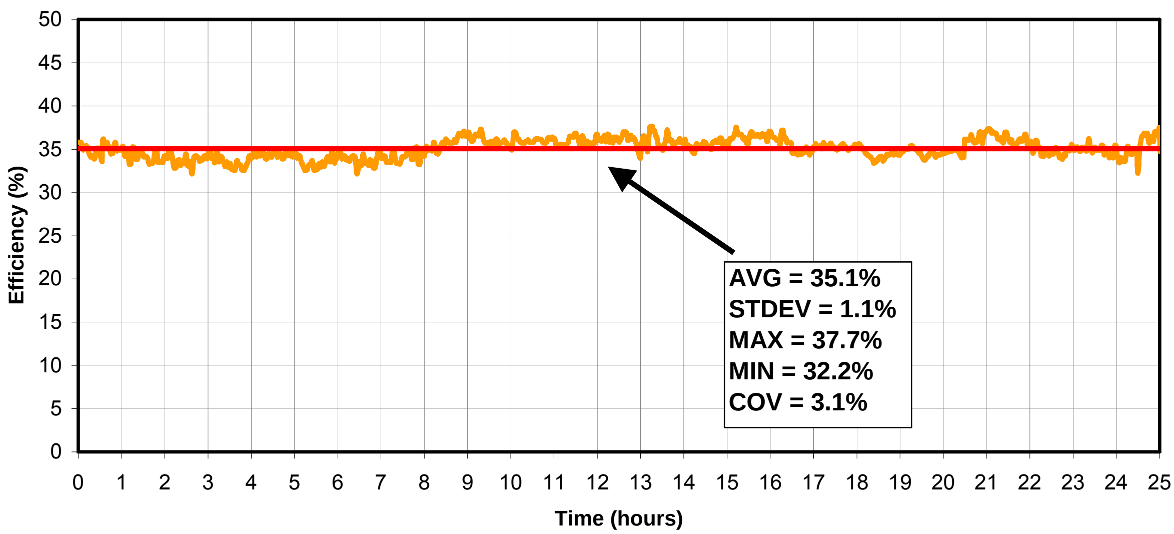


Figure 74 – Run D - Stable LFG Operation- 25 Hours Continuous

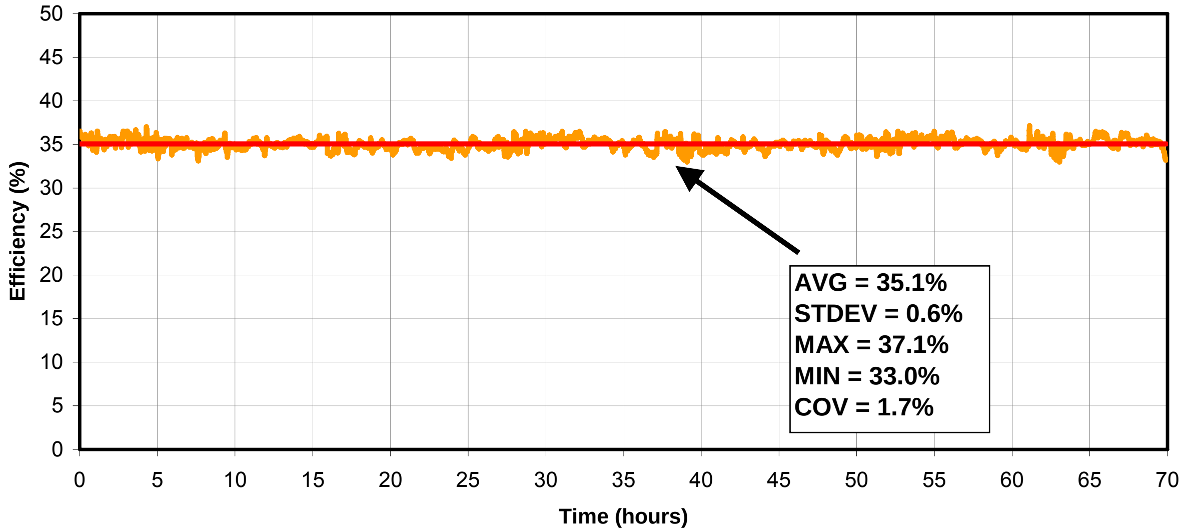


Figure 75 – Run E - Stable LFG Operation- 70 hours continuous

3.7.3.2 Control System and Engine Stability

The thermal control of the LFG HCCI system is the primary means to control ignition timing of the engine, and therefore to ensure stable operation. The system is designed with two heat exchanger systems to accommodate startup and steady state operation. The LTA (liquid to air) heat exchanger coupled with a hot oil pump and reservoir allow for the proper intake temperature at startup to be reached. Once the engine is producing exhaust hot gases, the LTA heat exchanger is bypassed, and thermal control is transferred to the ATA (air to air) heat exchanger. The required intake thermal energy comes from the waste heat generated by the engine.

To achieve the desired temperature, the position of a butterfly valve is adjusted to direct a smaller or larger portion of the air-fuel mix through the heat exchanger. The more air-fuel mixture is directed to the exchanger, the hotter the manifold temperature. The control system automatically adjusts the position of the butterfly valve to maintain the prescribed temperature. Figure 76 and Figure 77 illustrate for the two longest runs how this control scheme maintains the intake manifold temperature, contributing for the stable operation of the engine.

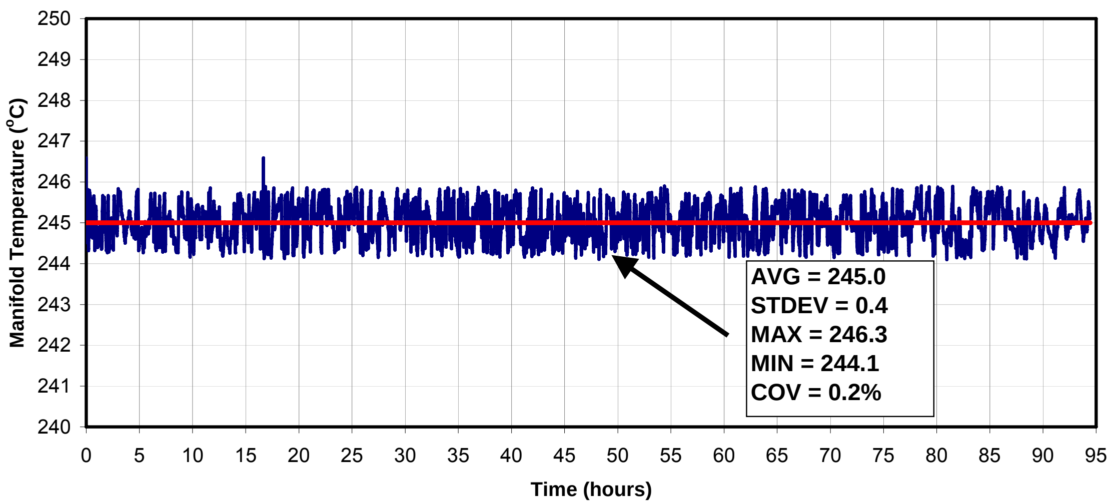


Figure 76 – Run A – Active Control of Manifold Temperature

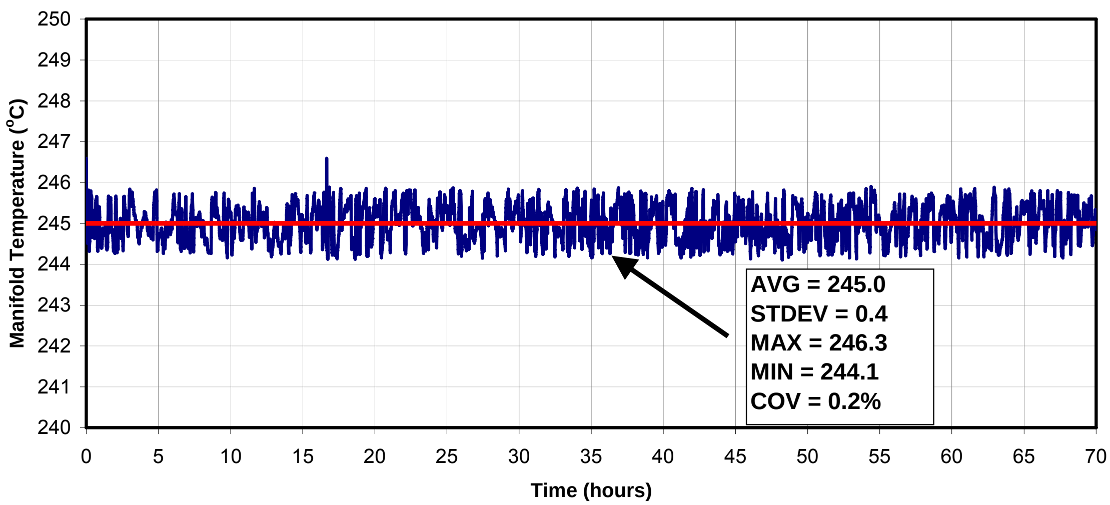


Figure 77 - Run E – Active Control of Manifold Temperature

ICTC (Individual Cylinder Temperature Control)

For optimization of power output and system efficiency, individual control of the inlet temperature to each cylinder is required. To supply each cylinder with a slightly elevated or decreased inlet temperature, the ICTC manifold was developed. The manifold provides individual heating and temperature monitoring for each cylinder. The control system automatically adjusts the individual cylinder, according to desired profile, defined during system optimization. Figure 78 illustrates the individual control of 3 of the 6 cylinders for run E.

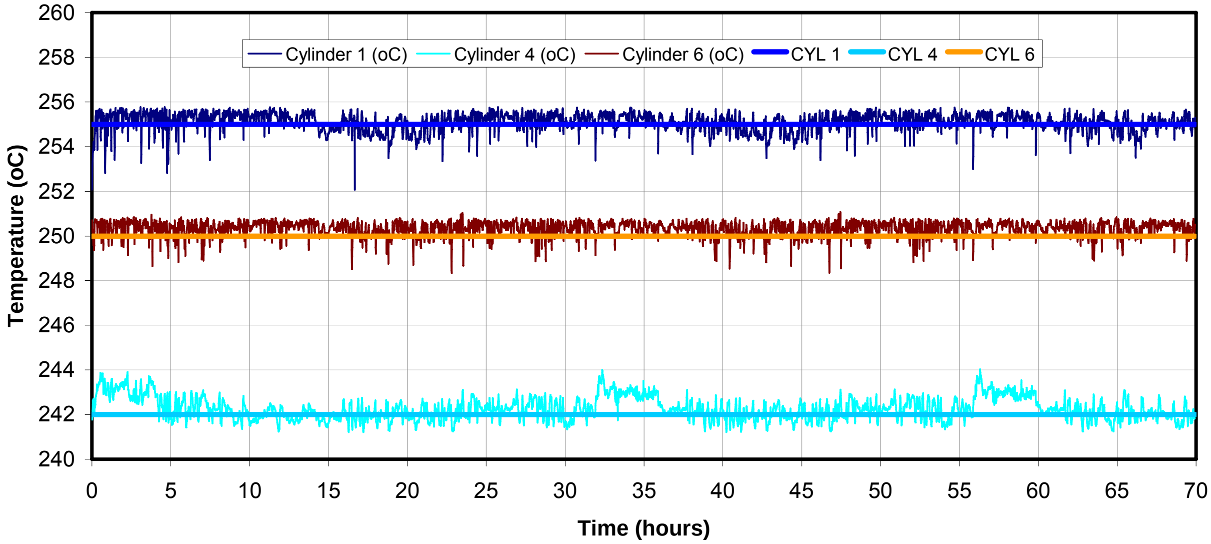


Figure 78 – Run E – Individual Cylinder Temperature Control

3.7.3.3 Effects of Ambient Conditions Fluctuations

From the long duration runs, it is evident that fluctuations of the ambient conditions DID NOT adversely affect the stability of the system. Figure 79 through Figure 83 plots show side-by-side the engine performance parameters (efficiency, NO_X and equivalence ratio) and the ambient conditions during the run (temperature, relative humidity and dew point) for runs A through E.

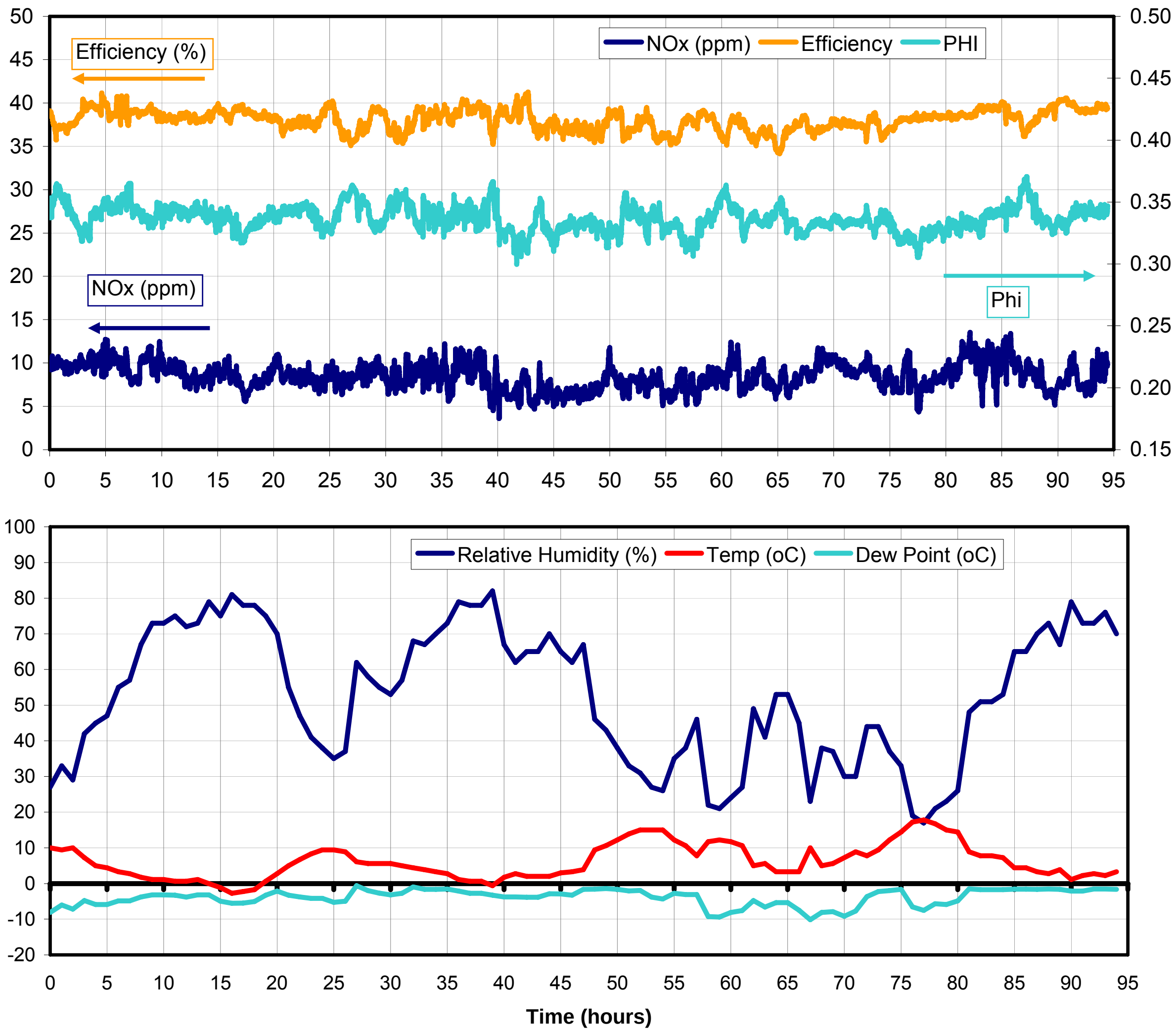


Figure 79 – Run A – Environmental Conditions during Run

Figure 79 shows the comparative plots for run A. This was the longest of the extended runs, and the ambient conditions varied greatly. For this run, the dew point varied from -10°C to -1°C (with relative humidity varying from 17% to 82%) and the ambient temperature varied from -3°C to 18°C. As the engine performance plot shows, there is no sign of instability due to the varying conditions.

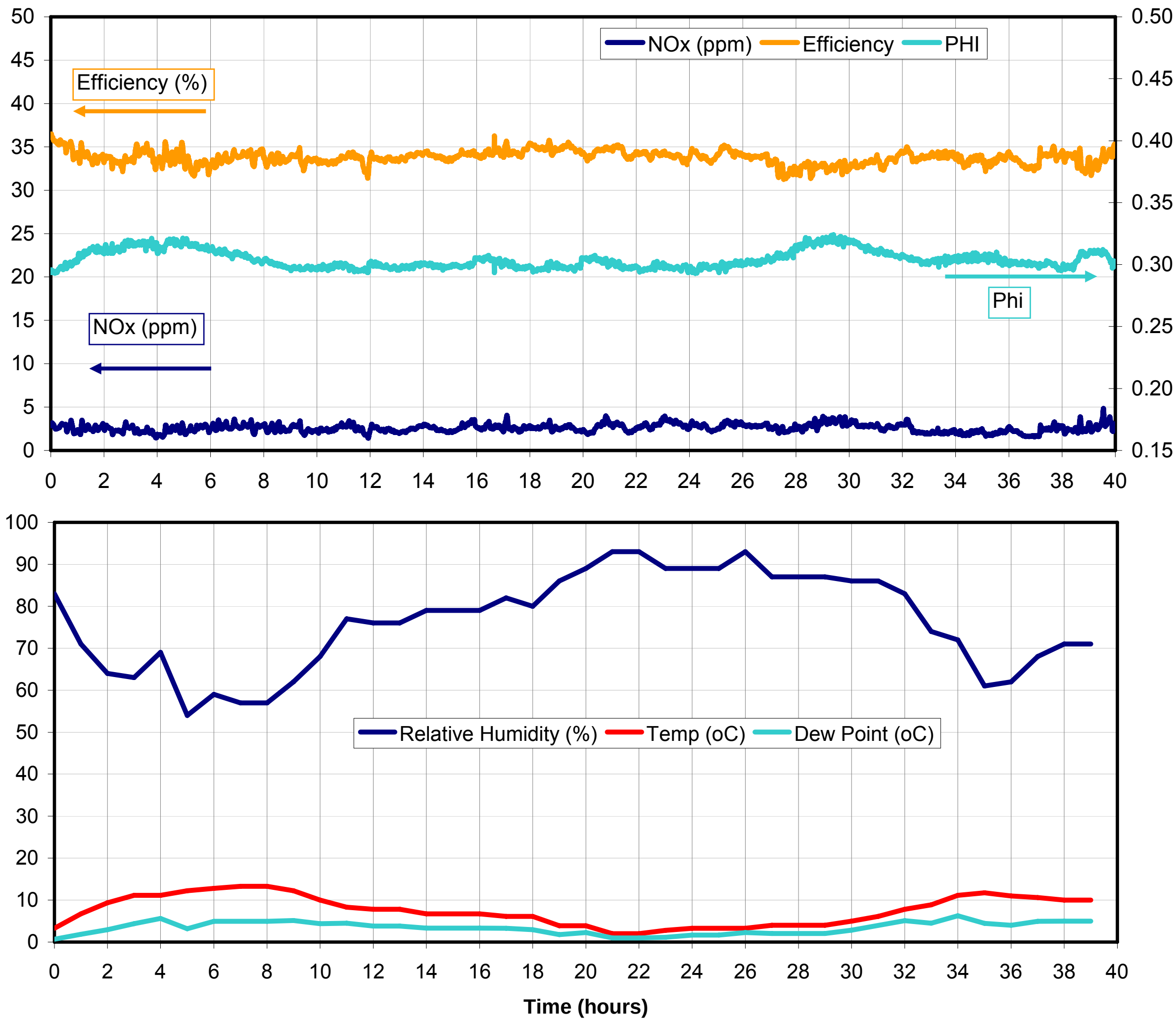


Figure 80 - Run B – Environmental Conditions during Run

Figure 80 shows the comparative plots for run B. For this run, the dew point varied from 1°C to 6°C (with relative humidity varying from 54% to 93%) and the ambient temperature varied from 2°C to 13°C. When compared with run A, the ambient conditions did not vary as much, but it shows operation at a higher range of dew points. Once again, there is no evidence of the ambient conditions affecting the system stability.

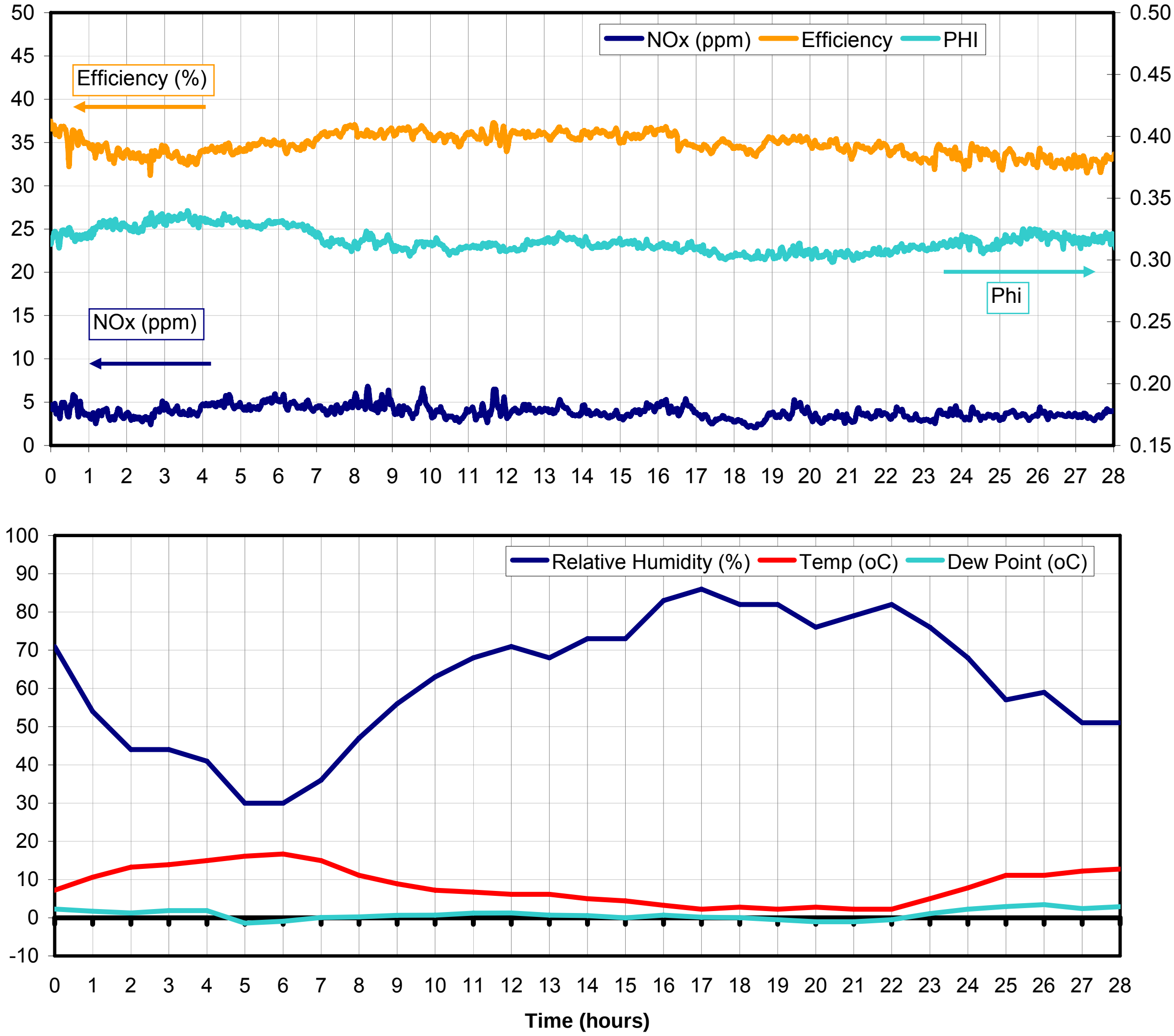


Figure 81 - Run C – Environmental Conditions during Run

Figure 81 shows the comparative plots for run C. For this run, the dew point varied from -1°C to 3°C (with relative humidity varying from 30% to 86%) and the ambient temperature varied from 2°C to 17°C. As with runs A and B, there is no evidence of the ambient conditions affecting the system stability.

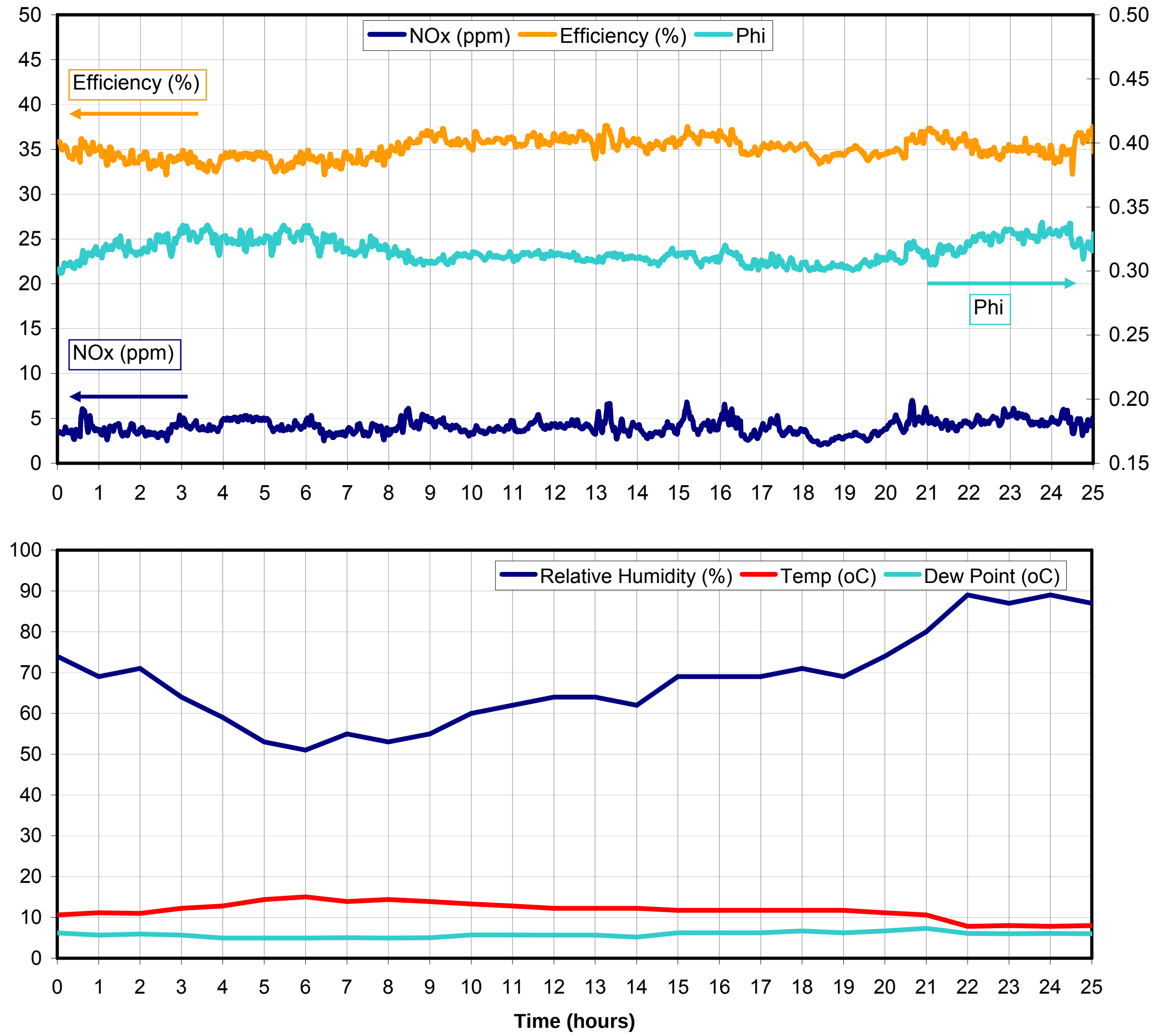


Figure 82 - Run D – Environmental Conditions during Run

Figure 83 shows the comparative plots for run D. For this run, the dew point varied from 5°C to 7°C (with relative humidity varying from 51% to 89%) and the ambient temperature varied from 8°C to 15°C. There is no evidence of the ambient conditions affecting the system stability.

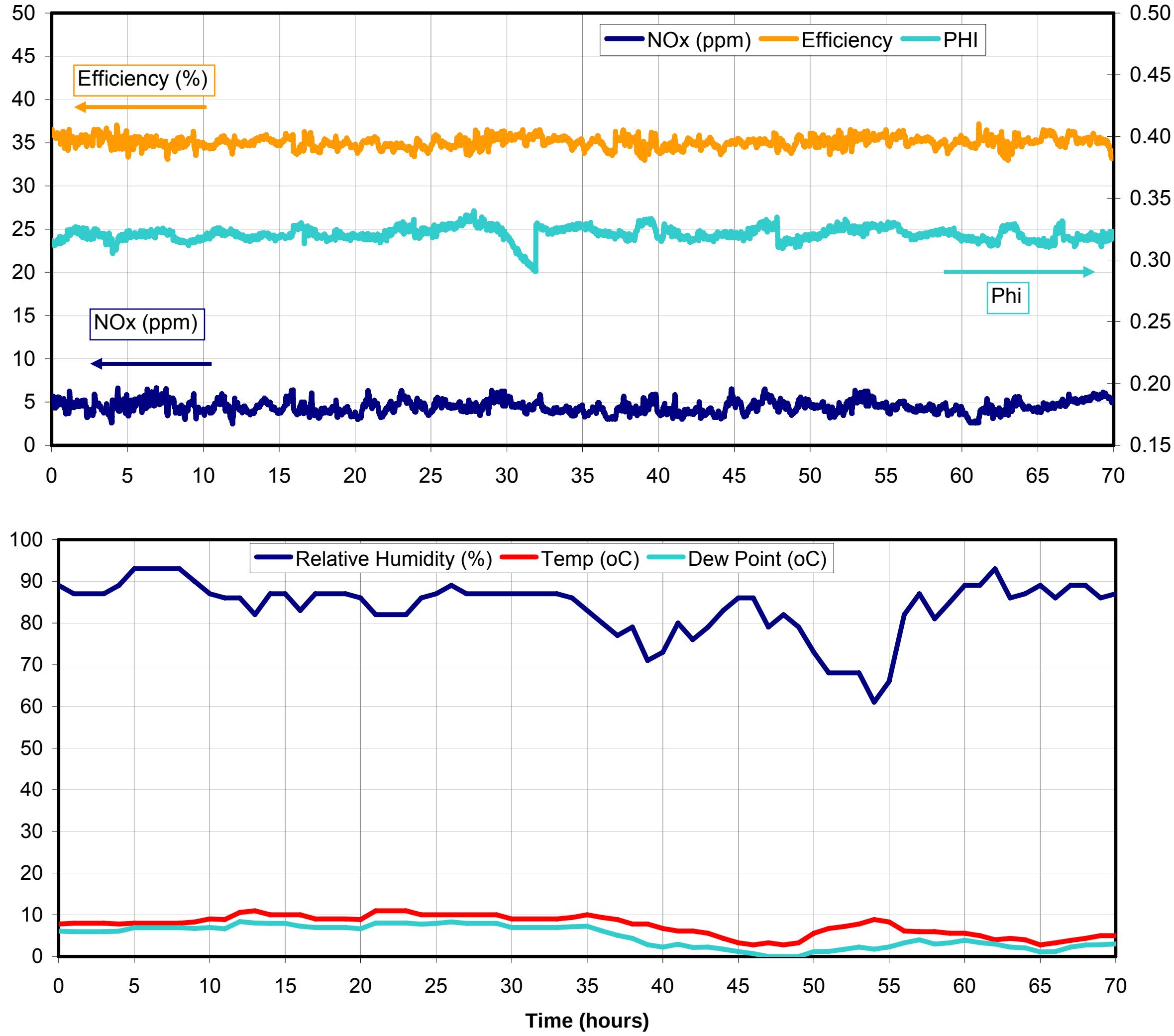


Figure 83 - Run E – Environmental Conditions during Run

Figure 83 shows the comparative plots for run E. For this run, the dew point varied from 0°C to 8°C (with relative humidity varying from 61% to 93%) and the ambient temperature varied from 3°C to 11°C. When compared with run A, the ambient conditions did not vary as much, but it shows operation at a higher range of dew points. Once again, there is no evidence of the ambient conditions affecting the system stability.

Concluding Remarks Regarding Ambient Condition Variation

Table 29 summarizes the environmental conditions variations during the extended runs. This illustrates the wide range of environmental conditions during these tests, and none affected the engine stability. While this does not cover all extremes of ambient conditions variation, the ability to maintain stability over these ranges without noticeable effects is a good indicator that the system is insensitive to typical environmental swings.

Table 29 – Summary of Ambient Conditions during Runs

Run	Ambient Temperature (^oC)		Dew Point (^oC)		Relative Humidity (%)	
	Min	Max	Min	Max	Min	Max
A	-3	18	-10	-1	17	82
B	2	13	1	6	54	93
C	2	17	-1	3	30	86
D	8	15	5	7	51	89
E	3	11	0	8	61	93
Overall	-3	18	-10	8	17	93
Variation	**21^{o}C**		**18^{o}C**		**76%**	

3.7.3.4 Landfill Gas Composition Variability

Table 30 summarizes the methane content for the LFG, during runs A through E. Normally, the LFG methane content varies slowly over the course of a day, and typically the variation range is small (see runs B through E). However, there are periods in time when there may be a more significant change, as illustrated in Table 30 for run A. Whether these are technical problems (e.g., leaks in the system) or natural occurrences, the engine would have to be able to absorb these differences. As evident from the results for run A, the engine is capable of stable operation even when the methane content of the LFG drops well below its typical values.

Table 30 – LFG Methane Content Variation during Extended Runs

Run	LFG Methane Content		
	Avg	Min	Max
A	36%	34%	36%
B	44%	42%	44%
C	44%	43%	45%
D	42%	42%	43%
E	44%	41%	46%
Overall		34%	46%

3.7.3.5 Transients during Startup

Engine start up takes 25-30 minutes. For stationary power applications, this represents a very small percentage of operating time, as such engines usually run continuously for periods in the order of 1000 hours. Therefore, these transients don't affect the overall efficiency of the system.

Description

During the first five minutes of operation, the engine is spinning electrically consuming power. As indicated in Figure 84a, when propane is introduced (about 5 minutes into the startup) the power goes from consumption to production. The efficiency while running on propane is stable at about 18% Figure 84b. At approximately 15 minutes into the startup, a blend of LFG and propane is fed to the engine. Note that the plot shows efficiency calculated in terms of propane and in terms of LFG. While the engine is running on a blend of propane and LFG, these efficiencies do not apply. Propane is slowly cutback while more LFG is slowly added until the engine reaches a stable operating temperature, usually at about 25 minutes. At this point, the engine is operating solely on LFG.

Temperature Control at Startup

Initially, the manifold set point is at 125^{o}C, for propane operation. At about 12 minutes into the startup, the manifold set point is changed from 125^{o}C to 255^{o}C, to transition to LFG. The control system's response to this set point temperature change is indicated in Figure 84c. It takes about 10 minutes for the inlet temperature to get from 125 to 255^{o}C. Once the manifold temperature reaches 255^{o}C, the set point may be readjusted, according to the run to be performed.

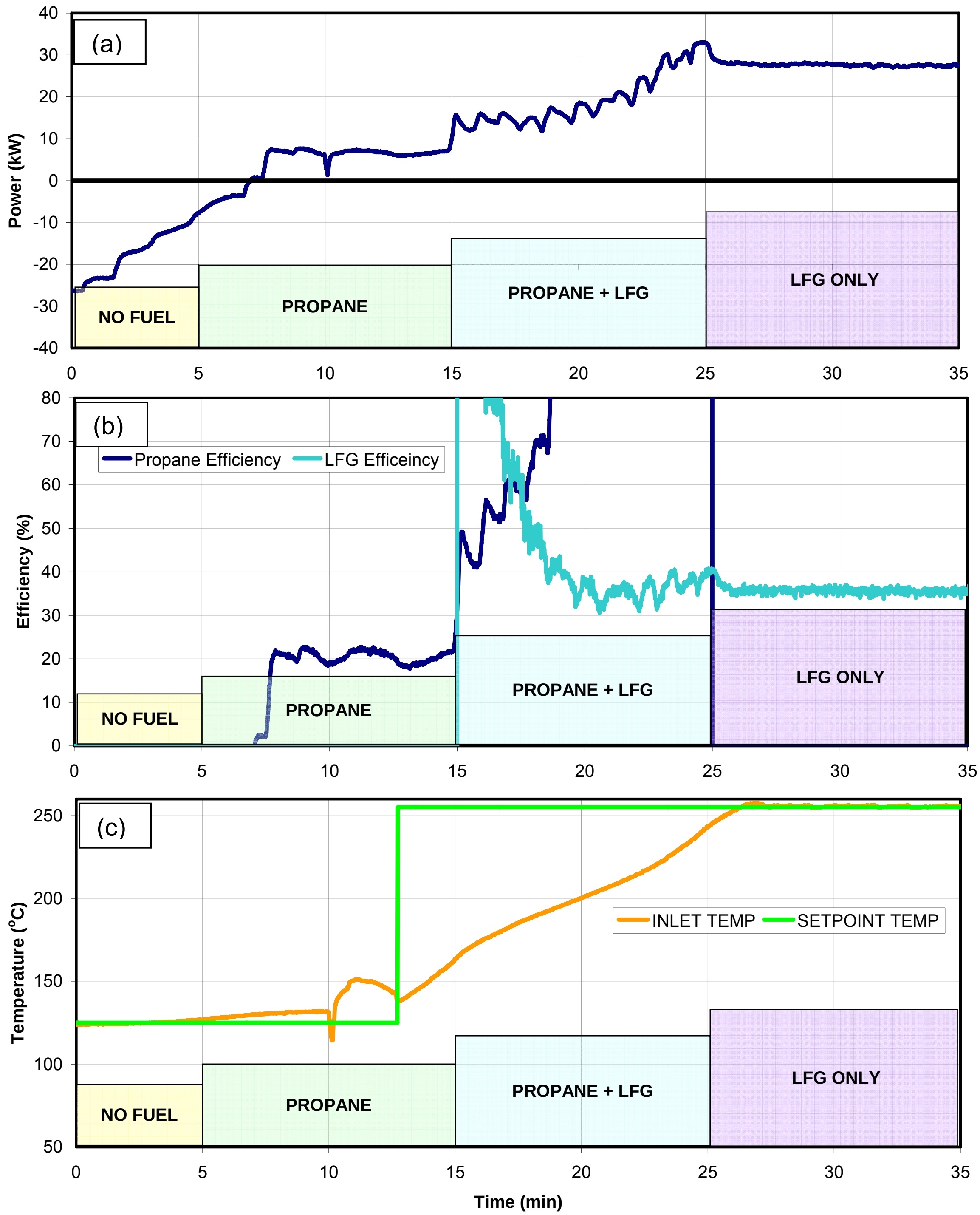


Figure 84 – Power (a), Efficiency (b), Inlet Temperature (c) during Transition to LFG

3.7.4 Durability Testing Results

Durability testing was conducted to verify that the HCCI genset, as a whole, could survive long periods of operation without degrading performance. It was also observed for indications of required replacement of components other than normal operation and maintenance.

As described in the Field Test Plan for monitoring engine durability, MEI performed inspections of the HCCI genset components. MEI's evaluation method included the following:

- Performance Monitoring
  - Operating parameter changes to maintain engine performance
- Visual Inspection
  - Observations and pictures of components
- Physical Inspection
  - Measurements of components

Additionally, MEI broke down the HCCI engine components into two categories: intended (manufacturer guaranteed) engine use and adapted engine use. These components are listed in Table 31.

Table 31 – Intended and Adapted Use HCCI Engine Components

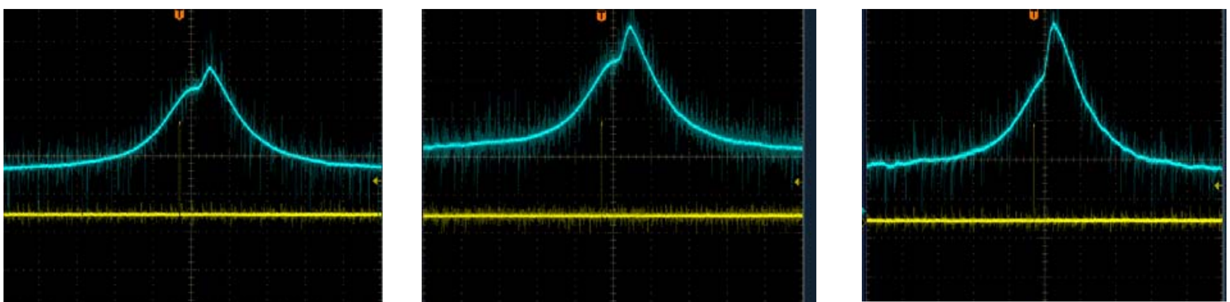
Item #	Intended Engine Use	Item #	Adapted Engine Use
1	CAT 3116 Engine	9	Heat Transfer Oil
2	Engine coolant	10	Cartridge Heaters-HTO
3	Engine oil	11	Cartridge Heaters- Trim
4	Radiator	12	Heat exchanger-LTA
5	Turbocharger	13	Heat exchanger-ATA
6	Electronics on Engine	14	Activated Carbon Filters
7	Generator	15	Electronics in Control Panel
8	Intake System Flex Hose		

3.7.4.1 HCCI Components for Intended Engine Use

Components of the HCCI genset which are intended for engine use have the same lifetime and maintenance interval as published by their respective manufacturers. See Appendix II of the Durability Testing Interim Report for CATERPILLAR 3116 truck engine maintenance and 15,000 hour overhaul schedule. To very that the engine was operating within manufacturer's specifications when operating in HCCI mode, MEI verified the in-cylinder peak pressure. MEI conducted oil testing at 30 hour intervals monitoring engine oil wear. Additionally MEI disassembled and inspected the engine and the turbocharger both prior to and after 510 hours of operation. The turbocharger was also inspected.

In-Cylinder Pressure Measurement

As part of engine operation during bench testing, “in-cylinder” feedback was implemented. Peak pressure was monitored and compared to top dead center (TDC) for cylinders 1, 3, and 6 utilizing OPTRAND model C82281-Q-CSTM pressure transducers. As the inlet temperature was increased for a given equivalence ratio, the peak in-cylinder pressure increased in magnitude. The peak pressure also occurred closer to top dead center (TDC). This is evidenced in Figure 85 A through C. Notice the increased magnitude and earlier peak timing. Firing timing swept from about 11.0 degrees of crank angle after TDC to about 8.5 degrees of crank angle after TDC. A typical “in-cylinder” pressure of about 37 ATM was noted during nominal running conditions.



(A)-33.0 ATM 11.0 Degrees after TDC

(B)- 37.0 ATM 9.5 Degrees after TDC

(C)- 39 ATM 8.5 Degrees after TDC

Figure 85 - Progression of In-Cylinder Pressure

The CAT 3116 engine is designed to handle in cylinder peak pressures of over 100 ATM. When operating in HCCI mode, the engine is being subjected less than half the forces it is designed for.

Oil Monitoring

Oil quality was monitored every 30 hours for signs of degradation. An eight ounce sample was pulled from the engine oil sump and send to Oil Analyzers, Inc. The normal oil change interval for a CAT 3116 engine is 250 hours. MEI has operated the HCCI genset for more than twice the CATERPILLAR suggested oil sample change interval without abnormal oil sampling results. Figure 86 shows plots for the iron, copper and aluminum levels in the engine oil over the 510 hour period. The corresponding dashed indicates the projected level of these metals up to 800 hours of operation. When the ppm level of these metals reaches the alarm limit, an oil change is recommended. According to the analysis performed, even after 510 hours of use, the oil is still considered "*suitable for continued use.*" From this analysis, it is concluded that the engine is not operating outside of recommended operation conditions. Furthermore, the recommended engine oil change interval for the HCCI genset is every 800 hours of operation.

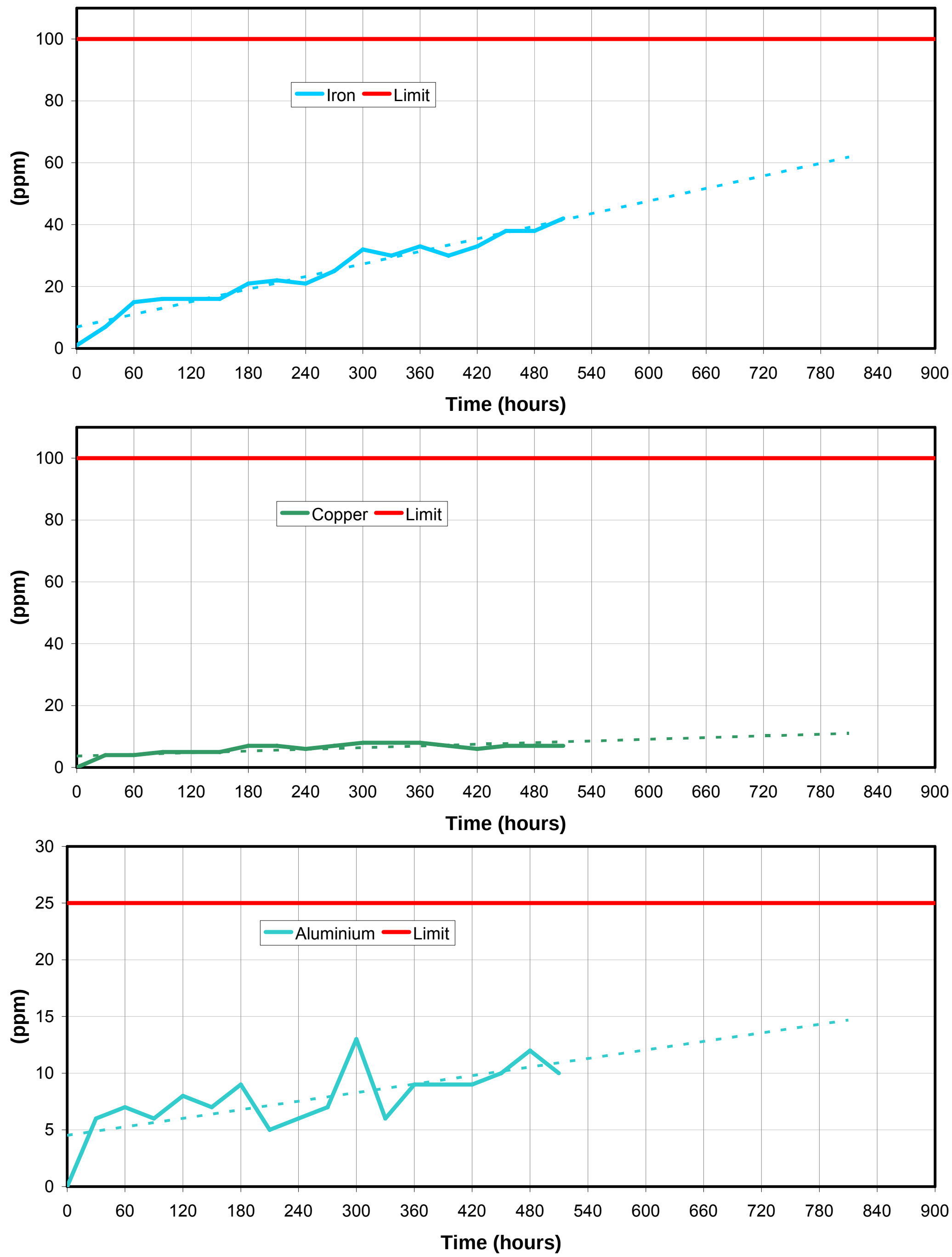


Figure 86 – Metal Wear During 510 hours of Operation

Visual Inspection

After operating the HCCI genset for over 500 hours, MEI pulled of the engine head to inspect the head, the cylinder walls as well as the turbocharger. Table 32 summarizes the condition of the components monitored. *No components* *show indication of abnormal or catastrophic wear.* Figure 87 shows the before and after pictures of the engine block. Figure 88 details cylinder #1 before and after LFG operation. All pistons are in like new condition and no pitting or scoring was noted on the cylinder walls for all 6 cylinders. Before and after pictures of the turbocharger are included in Figure 89. The engine is in excellent shape.

Table 32 – HCCI Engine Components Visual Inspection

Component	"0 hour" Condition	"510 hour" Condition
Block	Shiny new	Like new
Pistons	Shiny new	Like new, no cracking or pitting
Cylinders	Shiny new	Like new, no scoring
Head	Some pitting on cylinder 1, 5	No change noted
ICTC manifold	Good	No change noted
Turbocharger	Like new	Some darkening of turbine wheel
Hoses	Good, pliable, no cracking	Good shape. I-8 shows some cracking. Does not need replacement

Figure 87 – Engine Block, 0 hours (left) 510 hours (right)

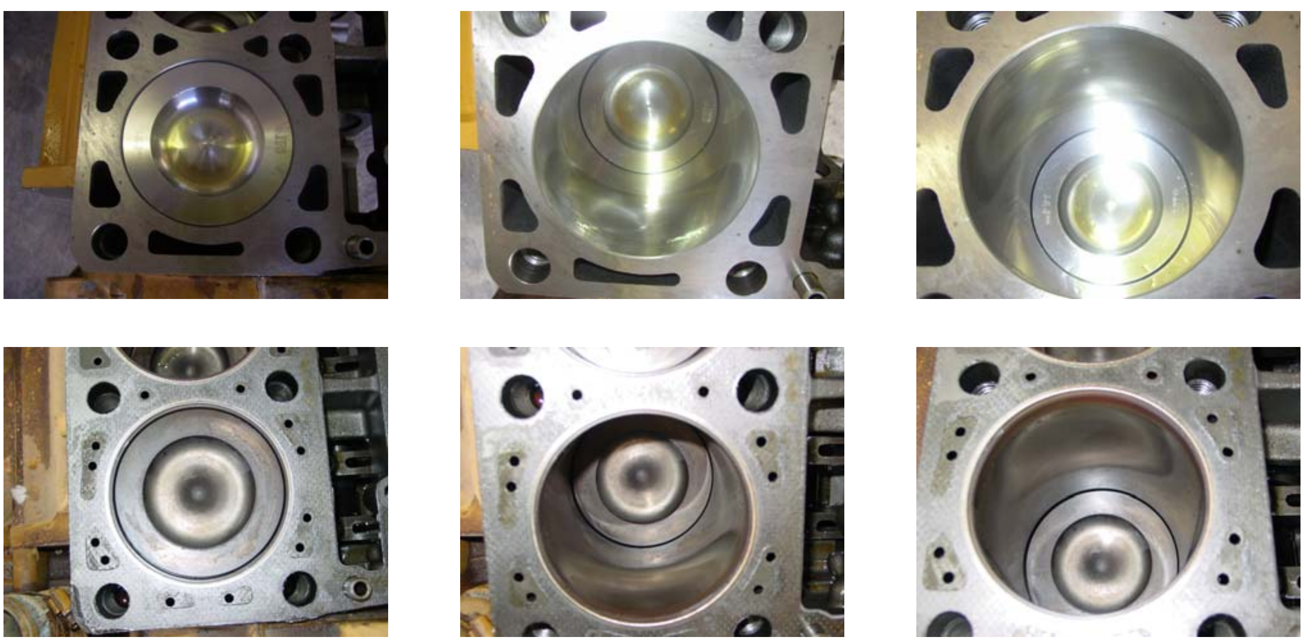


Figure 88 – Cylinder #1 0 hours (top)-510 hours (bottom)

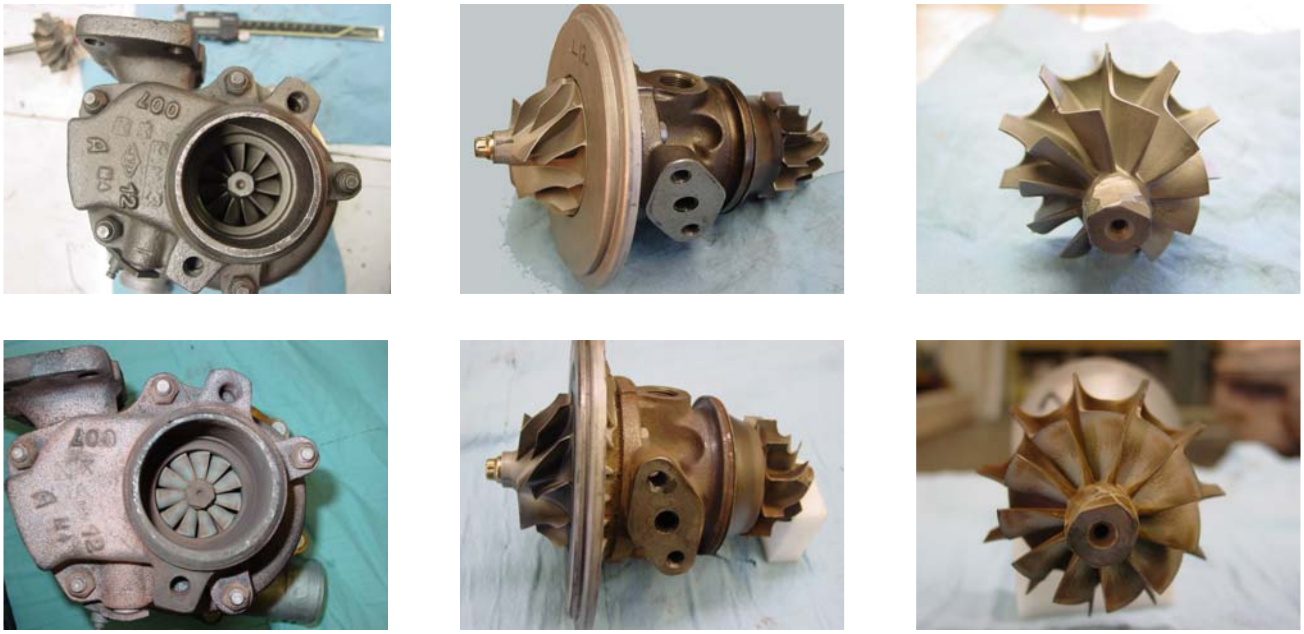


Figure 89 – Turbocharger @ 0 hours (top)-510 hours (bottom)

Physical Inspection

The components listed in Table 33 were measured after 510 hours of operation. The measurements were compared to CATERPILLAR'S specifications. *No components were found to be out of specification.*

Table 33 – Physical Inspection Results

Component:	Specification:	Method	Pass/Fail
Battery	12 Volt 1200 CCA	Meas	Pass
Main Bearing Set	Orig. Journal Size 3.5433 Undersize 3.5335 = .010 Undersize 3.5335 = .020	Meas	Pass
Rod Bearing Set	Original Journal Size 2.7559 Undersize 2.7461=.010 Undersize2.7362=.020	Meas	Pass
Pistons	Piston Skirt=4.1299 Orig.Clr.=.0049 Limit=.0090	Meas	Pass
Rings Set	Ring Gap =.0300 RingLandClr.=.003	Meas	Pass
Wrist Pins	Pin Dia.= 1.5748 WearLimit=.0010	Meas	Pass
Rebuilt Head/Valves/Guides	Pitting/excess clr=.005	Meas	Pass
Crank Seals	3.533 i.d.	Visual	Pass
Cylinder Sleeves	Orig. Bore = 4.1348 Max.wear=.0040	Visaul/Meas	Pass
Crankshaft Regrind	Orig. Journal Size=2.7759	Meas	Pass
Starter	Shorting or open circuits	Meas	Pass
Water Pump	Shaft play good to .005	Visaul/Meas	Pass
LTA Oil Heaters	20 ohms	Meas	Pass
Cartridge Trim Heaters	30 ohms	Meas	Pass
Engine Oil	Std oil testing	Meas	Pass
Oil Cooler	Clean--no sludge or scaling	Visual	Pass
Coolant	Spec. gravity / ph	Meas	Pass
Valve Adjustment	.015 int. .025 exh	Meas	Pass
Valve Guides	Valve Stem clr.= .0035 max.	Visaul/Meas	Pass
Compression Test	350 psi	Meas	Pass
Carbon Filters	Reduction in Siloxanes in LFG	Meas	Pass
Intake Heaters	Nominal resistance 30 OHM in Parallel	Meas	Pass

3.7.4.2 HCCI Components for Adapted Engine Use

MEI was able to determine a useful life for the "adapted" for engine use components by comparing the manufacturer's specification sheets to the applied use. Table 34 summarizes the component lifetime for the adapted engine components.

Table 34 –Adapted Use HCCI Engine Component Lifetime

Component	Lifetime (hours)
Heat Transfer Oil	>15,000
Cartridge Heaters-HTO	>12,000
Cartridge Heaters-Trim	>12,000
Heat exchanger-LTA	>20,000*
Heat exchanger-ATA	>20,000*
Activated Carbon Filters	>25,000
Electronics in Control Panel	>60,000 (replace as required)

Heat Transfer Oil

The Thermia C heat transfer oil is being used in accordance to Shell's recommendations. Its useful life is >15,000 hours (or >10,000 engine startups) at conditions it is used.

Cartridge Heaters

The cartridge heaters were selected for their heating capability as well as resistance to impact and vibration. According to Chromalox, both the 250 watt trim heater and the 1500 watt oil heater have a minimum life expectance of >12,000 when operated at full duty cycle.

Heat Exchangers

The liquid to air (LTA) heat exchanger is intended for industrial use. It has a recommended lifetime >20,000. The air to air (ATA) heat exchanger is intended to be a recuperater for industrial applications. It has an expected lifetime of >20,000 hours. For both heat exchangers, no performance degradation has been noted to date. They have been in operation for more than 1,500 hours in this application. It is recommended that they be checked for fouling annually. For a commercial HCCI genset, a compact, low cost heat exchanger such as the one pictured in Figure 90. This off the shelf part, manufactured by TRANTER, has an all stainless steel design and is capable of processing flows for over >15,000 hours without fouling concerns.

Figure 90 – Commercial Heat Exchanger

Activated Carbon Filters

Prior to operation on LFG and after 500 hours, MEI captured LFG samples both pre and post activated carbon filters. Using AT@ 71 sampling method (shown in Figure 91) for the presence of siloxanes, Air Toxics of Folsom, CA. performed laboratory analyses on the samples. Table 35 summarizes the findings of this testing. Only two of the 24 known siloxane species were present pre-filter in very low concentrations. *No siloxanes have been found post-filters*.

Figure 91 – AT @71 Siloxane Sampling

Table 35 - Results of Siloxane Species found in LFG Samples

Time (hours)	Gas species	Pre-filters	Post-filters
0	Octamethylcyclotetrasiloxane	570 (ppb)	None Detected
	Decamethylcylopentasiloxane	351 (ppb)	None Detected
510	Octamethylcyclotetrasiloxane	390 (ppb)	None Detected
	Decamethylcylopentasiloxane	190 (ppb)	None Detected

At the nominal flow rate of 25 cfm and given the siloxane species and concentration present, Carbtrol, the manufacturer of the activated carbon filters, estimated the useful life of one filter at >13,000 hours. The current installation using two filters (shown in Figure 92) in parallel reducing the nominal flow to less than 13 CFM and extending the useful life to >25,000 hours for the pair. Carbtrol also recommended sampling every 5,000 hours to ensure that breakthrough has not occurred.

Figure 92 – Carbtrol Activated Carbon Filters

3.7.4.3 Durability Testing Outcome

Through monitoring performance, physical and visual inspection, MEI verified that the HCCI genset is capable of operating for greater than 500 hours without issues. Using the intended lifetime for manufacturer guaranteed components and analyzing lifetime of the adapted components, the HCCI genset meets the program goal of >10,000 hours between major overhauls.

Revisiting the list of components for Intended and Adapted use, all components are expected to have >10,000 hours of operation before repair or replacement is required. Fluids and hoses are expected to be regular maintenance items.

Table 36 – Intended and Adapted Use HCCI Engine Components

Item #	Intended Engine Use	Life (hours)	Item #	Adapted Engine Use	Life (hours)
1	CAT 3116 Engine	15,000	9	Heat Transfer Oil	15,000
2	Engine coolant	6,000*	10	Cartridge Heaters-HTO	12,000
3	Engine oil	800*	11	Cartridge Heaters- Trim	12,000
4	Radiator	15,000	12	Heat exchanger-LTA*	20,000
5	Turbocharger	15,000	13	Heat exchanger-ATA*	20,000
6	Electronics on Engine	15,000	14	Activated Carbon Filters	25,000
7	Generator	15,000	15	Electronics in Control Panel	60,000
8	Intake System Flex Hose	6,000*			

*Indicates an regular maintenance item

3.8 Economic Performance

MEI plans to develop three different HCCI generator systems. Details of the planned systems are as follows:

- 30 kW Unit
  - Modular unit used as initial field tests and pilot operations
  - Based on CAT 3106 Engine Design
  - Configurable up to 150 kW
- 200 kW Unit
  - Potential Based On Cummins Engine Block
  - Suitable for MW size installations
  - Design is mostly scalable from 30 kW unit
- 750 kW Unit
  - Future Development – may require partner with engine manufacturer

3.8.1 Projected System Costs

MEI has broken the production of different generator systems up into three phases. MEI intends to manufacture the following:

- PHASE I -- 30 kW system (used in 150 kW Configuration)
- PHASE II -- 200 kW system (used in 600 kW Configuration)
- PHASE III – 750 kW system (single unit configuration)

MEI has estimated the following costs for each phase of genset development: prime mover cost, interconnection costs and annual operation and maintenance costs. Table 37 summarizes the costs associated with a Phase I production genset. Table 38 summarizes the costs associated with a Phase I production genset. Table 39 summarizes the costs associated with a Phase I production genset. All costs assume that a gas collection system is already in place.

Table 37 – Costs for Phase I HCCI Gensets

Input Values	Value	units
Prime Mover Cost (BOM)	18,000	dollars
Interconnection Cost	2,350	dollars
Engine Output	30	kW
Annual Service Costs (Labor)	1,978	dollars
Annual Service Costs (Materials)	3,891	dollars
Useful life	20	years
Operational days per year	328	days

Table 38 – Costs for Phase II HCCI Gensets

Input Values	Value	units
Prime Mover Cost (BOM)	80,000	dollars
Interconnection Cost	30,000	dollars
Engine Output	200	kW
Annual Service Costs (Labor)	3,726	dollars
Annual Service Costs (Materials)	25,147	dollars
Useful life	20	years
Operational days per year	328	days

Table 39 – Costs for Phase III HCCI Gensets

Input Values	Value	units
Prime Mover Cost (BOM)	200,000	dollars
Interconnection Cost	45,000	dollars
Engine Output	750	kW
Annual Service Costs (Labor)	7,186	dollars
Annual Service Costs (Materials)	62,757	dollars
Useful life	20	years
Operational days per year	328	days

Through continued HCCI engine development and volume production efficiencies, it is anticipated that the program cost targets of $0.05/kWh and $750/kW can be achieved. A summary of the anticipated cost for production HCCI genset's is in Table 40.

Table 40 – Levelized Cost of Electricity for HCCI Engines by Production Phase

Target Parameter	Program Goal	PHASE I	PHASE II	PHASE III
LCOE ($/kWh)	< $0.05	$0.047	$0.030	$0.018
Capital Costs - Prime Mover ($/kW)	< $750	$745	$640	$413

4.0 Conclusions and Recommendations

4.1 Conclusions

At the beginning of this project, most HCCI engines had been operated in laboratory environments. Field testing of this LFG fueled HCCI demonstration engine has allowed for optimization of an engine to operated in HCCI mode. By working through the several configurations, MEI has established the necessary operating conditions to meet the program goals. Utilizing natural gas for this “tuning” of the engine allowed for testing to continue using simulated landfill gas. MEI has expanded the understanding of HCCI mode of engine operation allowing for the transition from natural gas to simulated landfill gas to eventually landfill gas as a fuel source.

The HCCI genset was operated using LFG as a fuel for 510 hours. Efficiency testing demonstrated that the genset meets project goals for efficiency and emissions. The HCCI genset meets the project goals for stability as well. To demonstrate stability, five long duration runs and sixty daily runs were performed. Stability tests were performed at three different efficiencies, with repeated tests at the optimal efficiency versus NO_X conditions. The HCCI genset operated below 5 ppm (0.07 lb/MW-hr) NO_X emissions with about 35% system efficiency. Higher system efficiency was also achieved; resulting however at slightly increased NO_X emissions levels. Lower NO_X emissions were achieved (3 to 4 ppm) with slightly lower system efficiencies.

Testing also demonstrated that the control system in place maintains the intake at prescribed temperatures, therefore controlling ignition timing and ensuring stable operation. There are two main levels of temperature control, one to control the bulk intake temperature, and the second level, targeting optimization, is the individual control of each cylinder intake to a prescribed profile. Results of both levels of control were presented. While all testing took place with an attendant monitoring operating conditions, switching to an unattended mode would require a few software modifications and minor hardware modifications in the control system.

The long duration runs ranged from 25 to 95 hours, during which there was significant variation of the ambient condition. As the results showed, the engine stability remained unaffected by the variations in ambient temperature, dew point and relative humidity. Results also demonstrated that the engine can operate at LFG methane contents much lower than the nominal content, without affecting stability. Using the intended lifetime for manufacturer guaranteed components and analyzing lifetime of the adapted components, the HCCI genset meets the program goal of >10,000 hours between major overhauls.

Testing results demonstrated that the HCCI genset meets project goals for efficiency, emissions, stability and durability. Operation on LFG had the following results:

- System Efficiency
  - ~35%-nominal (peak ~39%)
  - Program Target 35% or greater

- NO_X Emissions
  - ~5.0 ppm-nominal with 35% efficiency
  - Peak ~13.0 ppm at peak efficiency
  - Program Target 5.0 ppm or lower

- Power Output
  - ~26 kW-nominal (peak ~29 kW)

- Stability
  - <5% variation
  - Program target <10%
- Durability
  - >12,000 hours
  - Program target >10,000 hours between overhauls

4.2 Recommendations

4.2.1 Technical/Design Recommendations

While the HCCI genset meets project goals while operating on landfill gas as fuel, MEI recognizes that a few design modifications could enhance engine performance. Prospective to improvements to the HCCI genset include

1. More appropriately sized generator (75 or 80 kW rather than 150kW
   - Less inertia to overcome
2. Larger diameter intake ducting
   - A large diameter on the intake ducting would reduce pressure drop
3. Instrumented engine head
   - The addition of in-cylinder instrumentation (ION SENSING) would allow for a more accurate determination of cylinder firing
4. Higher compression ratio (16.7:1 currently)
   - Developing a piston/head arrangement that allowed for a higher compression ratio would improve efficiency.
5. Larger engine (6.6L currently
   - Moving to a larger engine would allow for increased power output

4.2.2 Recommendations towards Commercialization

Successfully operation of a demonstration HCCI genset using landfill gas, marks the next step towards a commercial HCCI genset. As part of the commercial development of this HCCI genset, MEI recommends that other similar facilities install and perform testing to demonstrate the viability of this technology for each specific site. MEI is in the process of making this size genset (30kW) commercially available as a demonstration engine. Initially these sites will benefit from electrical power savings by offsetting some of their electrical usage. A larger 200kW version is being developed.

4.2.2.1 Commercialization Potential

The production HCCI genset will be based upon readily available diesel engines. During the MEI manufacturing process, these engines will be modified to operate in HCCI mode. Materials can be purchased at commodity prices from outside vendors. Figure 93 and Figure 94 show a CAD model and the actual HCCI Demonstration system. Production HCCI Gensets will be either skid mounted for permanent installations or trailer mount for temporary applications. Figure 95 shows these versions of the genset package.

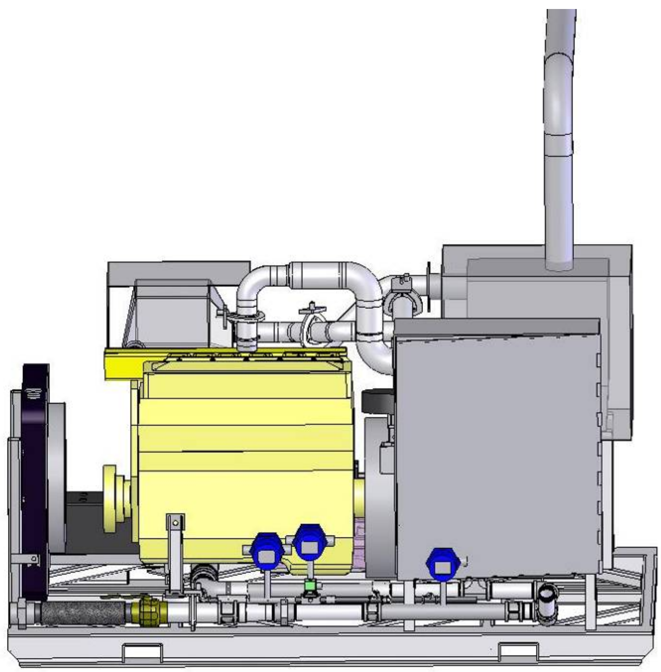


Figure 93 - CAD model of Demonstration HCCI Genset

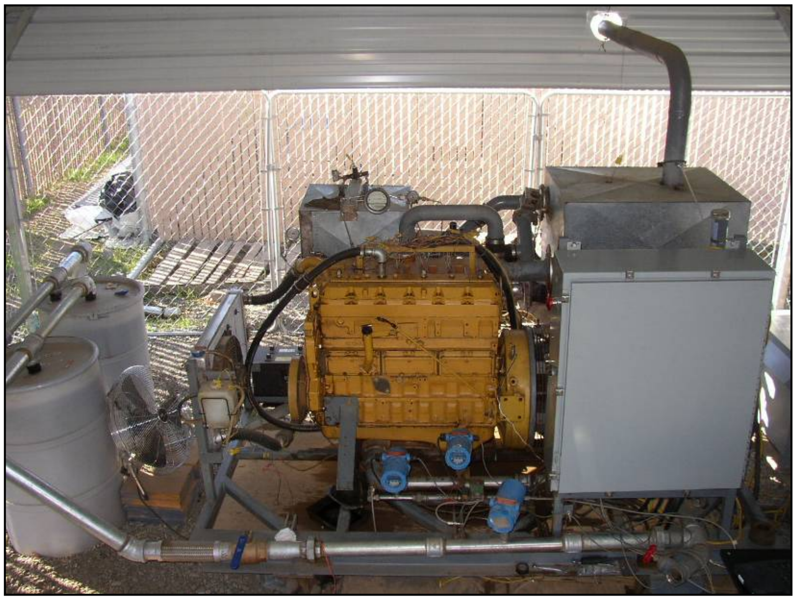


Figure 94 - Actual Demonstration HCCI Genset

Figure 95 - Commercial HCCI Genset-Skid Mount and Trailer Mount

This multiple-step manufacturing operation will be split into two phases. Phase I is the procurement of off-the-shelf engine and engine components. The Phase I steps while critical are not proprietary and thus can be cost-effectively contracted to outside engine manufacturers. Phase I operations for low-volume manufacturing will be directed by Makel Engineering.

Phase II manufacturing encompasses the proprietary operations of MEI engine technology. These operations have successfully been conducted at MEI for a developmental engine. In the future, these functions can be scaled for low-volume production of 100-200 units per year. The facilities and capital equipment to support this volume of production include 50,000 sq feet of open bay manufacturing space, machine tools, load banks, test cells (four dedicated for production, one dedicated to R&D), emissions monitoring equipment, electrical interconnect equipment, and quality assurance equipment. As the production demand exceeds 200 units per year, MEI will seek to secure relationships with contract manufacturers and/or license the technology to OEMs.

Key milestones to complete the production development plan include:

- Extended field test trial with the 30 kW system (18 months ~ $200K)
- 200 kW system development (18 months ~ $1.0MM)
- Product design/packaging (24 months ~ $1.5MM)
- Prototype production of 10 units (12 months ~ $1-2MM)

4.3 Benefits to California

The benefits of RD&D efforts in HCCI Genset technology include:

- Improving air quality
  - Using Landfill gas (removes CH4 from) environment potent greenhouse gas
- Reduce operational costs of end user
  - Offsetting the cost of electricity for municipalities and other end users

This technology can be adopted very quickly by a wide array of potential sites where sources of low BTU value feed stocks are present. These sites include:

- Landfills
- Waste Water Treatment Plants
- Dairies
- Biomass Gasification Plants

Additionally due to the very low emissions of this engine, pollutants are reduced relative to other forms of power generation:

- Improve environmental conditions for the local communities in which air quality issues exist
- Improve the power independence for the state
- Reduce costs for end use authorities
- Increase revenue for landfill authorities

Landfills, Waste Water Treatment Plants (WWTP), Dairy and Gasification methane production plants often are too small to justify installation of large engines for generation and export of electric power. Such facilities burn the methane gas (diluted with nitrogen or carbon dioxide) in a flare. Installation of HCCI engines, such as the demonstration engine shown in Figure 96, at landfills and other municipalities across California can improve the quality and reliability of power supply, and will provide environmental benefits. Utilizing landfill gas as a fuel rather than burning it off, as shown in Figure 97, reduces reliance on fossil fuels, while producing very low emissions.

Figure 96 –Clean Burning HCCI Genset for Power Generation

Figure 97 –Flare stack (left), 24 Burners Flaring Off of Landfill Gas inside Stack (right)

References

1 Aceves, S. M., Flowers, D., Martinez-Frias, J., J. R. Smith, J.R, Dibble, R. W., Au M., and Girard, J. W., 2001, “HCCI combustion: analysis and experiments” SAE Pare No. 2001-01-2077.

2 Aceves, S.M., Smith, J. R., Westbrook, C. K., and Pitz, W. J., 1999, “Compression ratio effect on methane HCCI combustion,” Journal of Engineering for Gas Turbines and Power, 121:569-574.

3 Fiveland, S. B and Assanis, D. N., 2000, “A four-stroke homogeneous charge compression ignition engine simulation for combustion and performance studies,” SAE Paper No. 2000-01-0332

4 Martinez-Frias, J., Aceves, S. M., Flowers, D. L.,. Smith, J. R., and Dibble, R. W., 2000, “HCCI engine control by thermal management,” SAE paper No.2000-01-2869.

5 Blizman, B., Makel, D. B., Dibble, R. W., and Mack, J. H., “Landfill Gas Fueled HCCI Demonstration System,” Proceedings of ICEF2006, paper number ICEF2006-1578

6 Pulkrabek, W.W., 1997, “Engineering Fundamentals of the Internal Combustion engine,” Prentice Hall Upper Saddle River, NJ, Chap. 2,3 and 9.

7 Makel Engineering, Inc., Grant PIR-02-003 - Bench Test Plan

8 Makel Engineering, Inc., Grant PIR-02-003 - Natural Gas Baseline Testing Interim Report

9 Makel Engineering, Inc., Grant PIR-02-003 - Simulated LFG Testing Interim Report

10 Makel Engineering, Inc., Grant PIR-02-003 - Report on the Installation of LFG Collection System

11 Makel Engineering, Inc., Grant PIR-02-003 - Report on the Installation of Delivery Manifold

12 Makel Engineering, Inc., Grant PIR-02-003 - Report on the Installation of Engine and Instrumentation

13 Makel Engineering, Inc., Grant PIR-02-003 - On-site Engine Performance Interim Report

14 Makel Engineering, Inc., Grant PIR-02-003 - Field Test Plan

15 Makel Engineering, Inc., Grant PIR-02-003 - Efficiency Testing Interim Report

16 Makel Engineering, Inc., Grant PIR-02-003 - Stability Testing Interim Report

17 Makel Engineering, Inc., Grant PIR-02-003 - Longevity Testing Interim Report

18 Makel Engineering, Inc., Grant PIR-02-003 - Technology Transfer Plan

19 Makel Engineering, Inc., Grant PIR-02-003 - Production Readiness Plan

Glossary

Abbreviation	Description
A/F	Air to Fuel
ATA	Air to Air
ATM	Atmosphere
BTE	Brake Thermal Efficiency
CAT	Caterpillar
CO	Carbon Monoxide
CO_2	Carbon Dioxide
E-STOP	Emergency stop
GC	Gas Chromatograph
HCCI	Homogeneous Charge Compression Ignition
HTO	Heat Transfer Oil
ICTC	Individual Cylinder Temperature Control
KGPH	Kilograms per hour
kW	Kilowatt
LFG	Landfill Gas
LTA	Liquid to Air
MAP	Manifold Absolute Pressure
NG	Natural Gas
NO_x	Nitric Oxide/Nitrogen Dioxide
NRL	Neal Road Landfill
O_2	Oxygen
PM	Particulate Matter
RPM	Revolution Per Minute
SI	Spark Ignition
SLFG	Simulated Landfill Gas
TDC	Top Dead Center
UHC	Unburned Hydrocarbon

Symbol	Description
η	Eta (efficiency)
Φ	Phi (Equivalence ratio)